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ABSTRACT

This teacher's guide suggests activities that provide opportunities for upper elementary students to explore, by direct experimert, many of the properties of light. Equipment is listed and construction of a light source is detailed. Instructions are given for setting up a classroom with electrical equipment. Activities are described in units dealing with mirrors, colored light, and refraction. (CS)

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ED 196 657

Teacher's Guide for

OPTICS

Elementary Science Study

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The Optics Unit

Teacher's Guide for Optics

Two Light Sources and Accessories for Optics – It is suggested that 3 of these packages be used with a class of 30 students.

Related Units

Colored Solutions
Daytime Astronomy
Light and Shadows
Mirror Cards

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PREFACE

The Elementary Science Study is one of many curriculum development programs in the fields of science, social studies, and mathematics under preparation at Education Development Center, Inc. EDC (a private nonprofit organization, incorporating the Institute for Educational Innovation and Educational Services Incorporated) began in 1958 to develop new ideas and methods for improving the content and process of education.

ESS has been supported primarily by grants from the National Science Foundation. Development of materials for teaching science from kindergarten through eighth grade started on a small scale in 1960. The work of the project has since involved more than a hundred educators in the conception and design of its units of study. Among the staff have been scientists, engineers, mathematicians, and teachers experienced in working with students of all ages, from kindergarten through college.

Equipment, films, and printed materials are produced with the help of staff specialists, as well as of the film and photography studios, the design laboratory, and the production shops of EDC. At every stage of development, ideas and materials are taken into actual classrooms, where children help shape the form and content of each unit before it is released to schools everywhere.

ACKNOWLEDGMENTS

I would like to acknowledge the continual stimulation and insights provided by the staff of ESS during the development of this unit. Particular thanks go to Malcolm Skolnick for encouragement as I began this work, and to Rosly Walter and Christopher Hale for their work in guiding the unit through the stages which I was unable personally to oversee. The unit reflects design ideas from many people, and Winfield Benner and the personnel of the EDC Carpentry Shop and Design Lab have all constructively influenced its present form. I thank them all for their interest and involvement.

I am indebted to many teachers from the Lexington (Massachusetts) School System for the opportunity to try out my ideas in their classes when the unit was in its earliest stage of development. The interest and help of Eugene Trainor during this period is especially acknowledged.

As the unit developed, teachers from many schools have taught it and have provided me with very valuable suggestions and comments.

Finally, special thanks go to Adeline Naiman for helping me improve the clarity and style of this *Guide*.

Robert V. Lange

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INTRODUCTION

The intent of this unit is to provide equipment with which students can notice and analyze, by direct experiment, many of the interesting properties of light. By providing them with the opportunity to carry out their own demonstrations and explorations and by helping them to inquire more than superficially about what they are doing, OPTICS gives students a chance to look at light itself and its interaction with matter. In doing this, children also are exploring why the world looks the way it does to us—that is, what the properties of light have to do with our visual experience. Finally, and not of least importance, OPTICS tries to stimulate children to develop their critical powers by providing them with situations in which their curiosity and thoughtful inquiry are rewarded with new understanding and insight about how the world works and how they work.

Following the *Guide* strictly is not the only—or indeed the best—way to teach this unit, nor is this unit the only or best way to "teach light." Your students will choose to emphasize what interests them and to pursue interesting digressions.

You can pick and choose from among the activities suggested in this *Guide*. You don't have to know the physical laws underlying the work of the unit, but it does help to be very familiar with the equipment and what it can do. The more time you spend on your own with it, the more the equipment can, in fact, help you to teach. In particular, you will find it useful to have the equipment with you when you go through the *Guide* yourself for the first time.

Ages and Scheduling

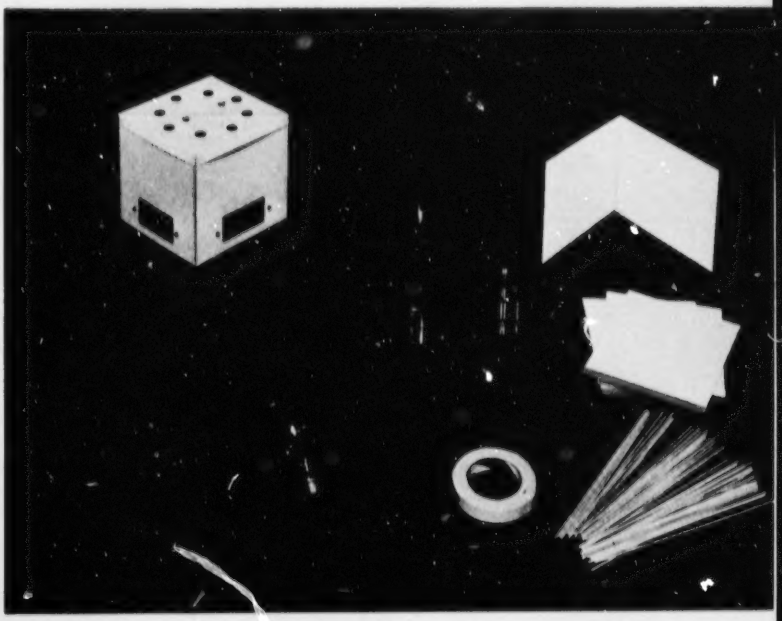
OPTICS has been taught primarily in fourth, fifth, and sixth grade and in one third grade class, and has even been tried with high school students. The younger the students, the more time they liked to spend in rather free exploration. Fourth graders found lots to do with little direction, while the high school students, presumably because of their school habits, needed explicit instructions from the very beginning. You may find the activities in Sections VII to IX most suitable for older students. For any of the middle grades, you can spend at least ten or twelve hours covering the activities in this *Guide*. Scheduling two one-hour sessions per week is reasonable.

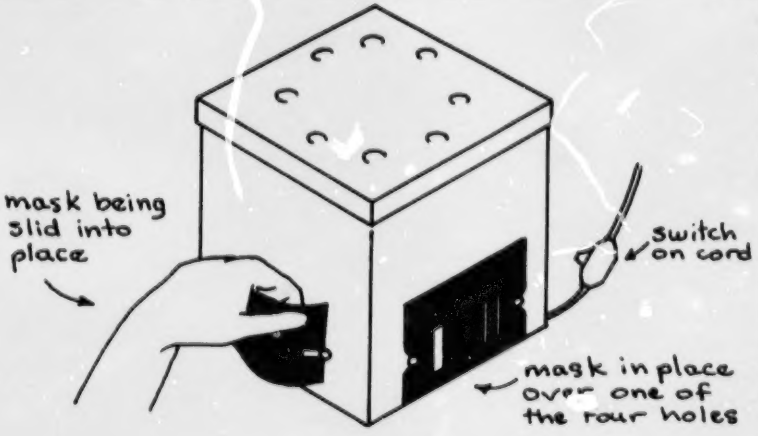
EQUIPMENT

The materials in OPTICS come in a kit labeled *Two Light Sources and Accessories for Optics*. You will need three such kits for a class of 30 students. The contents of a kit are listed below.

Two Light Sources and Accessories for Optics
- 2 light sources
- 2 light bulbs
- 24 metal mirrors
- 24 mirror supports
- 24 probe sticks
- 8 screens
- 52 masks (see pages 3–4)
- 12 combs
- 8 small, round, clear containers, with tops
- 4 medium, round, clear containers, with tops
- 2 large, round, clear containers, with tops
- 1 roll of masking tape
- 1 9-ft heavy-duty extension cord with triple outlet

You will also need to supply granulated sugar (salt can be substituted), paper cups, and spoons to measure the sugar with.





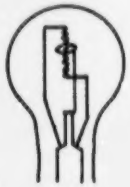
Source

Because each student should have his own beams with which to work, the central piece of equipment in this unit is a light source. You will need one source for every five or so students in your class.

Each source consists of a special (but readily available) 200-watt light bulb, mounted in a square cardboard holder. Each holder has four large holes spaced evenly around its sides. The masks (described on pages 3–4) are slid down over these large holes to produce the various sets of beams

to be used. The round light sources shown in the photographs are the Trial Teaching equipment. The new square light sources function in exactly the same way.

The filament of a new bulb is straight and looks like this:

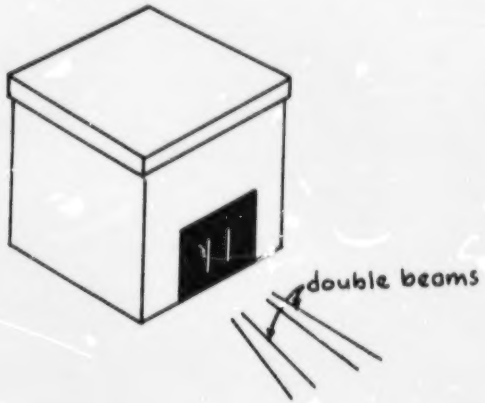


Because of the position of the filament of the bulb with respect to the masks, distinct beams are produced. If the beams from the source develop indistinct edges, this is probably due to a deterioration of the bulb. An inspection of the bulb may reveal that the filament looks like this:

A bulb with a curly filament must be replaced. These bulbs can be purchased at electrical supply houses. Be sure that you ask for a *General Electric* 200A clear bulb *with axial filament*. Other brands tried have been found to be inferior.

Most bulbs will last for many hours, and a class may easily get through all the work in this *Guide* before any replacement is required.

Even when the bulb is all right, you may notice that some narrow beams are double:



The double beam is produced by reflections in the bulb. The light coming directly from the bulb filament through the mask slit produces the primary beam. Light which has reflected off the inside of the bulb glass produces the extra beam. If this is annoying, the only remedy is to block off the unwanted half of a beam with some object, such as one of the mirrors provided with the unit.

Masks

Six different types of masks are provided. Each fits over one of the holes in the source. Any four masks or combination of masks can be used with one source at a time. This enables up to eight students to work at the same source, singly or in pairs. Several masks of each type are supplied, as indicated.

Of course, new masks like these six—or of some other design—can be cut from any paper heavy enough to stop the light.

Mask 1 provides a variety of beams useful for exploratory work in both reflection and refraction. These activities are described in Sections I and VII. Narrow beams emerge from the vertical slits, and a wide beam from the vertical hole.

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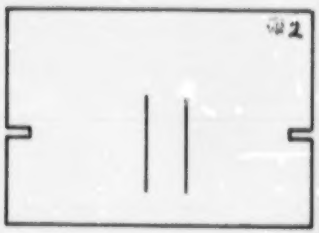
Mask 2 produces two narrow beams of light, which are convenient for use in Section II, particularly, but which may be useful to students at other times as well. If only one beam is being used, the other may be blocked off with a mirror or a piece of dark paper.



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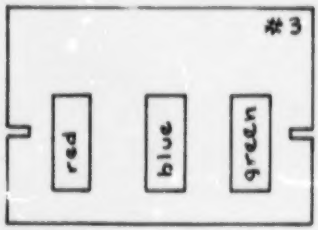
Mask 3 provides the distinct colored beams required in Section IV.



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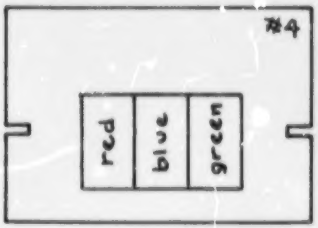
The three colored beams produced by mask 4 are wider and convenient for aspects of Section VI.



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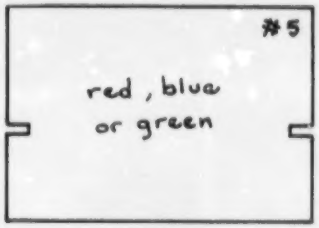
Mask 5 is simply a single piece of colored plastic to be used as a whole to provide one large, colored patch of light (Section VI). It may also be useful to you or your students in contexts having nothing to do with the source or the material in the *Guide*. That is, if you would like a large piece of colored plastic for some other work with light or color, here it is.



12: 4 red, 4 blue, 4 green

Mask 6, opaque black paper, can be used to cover over a hole not being used. Your students can also cut these masks to produce some combination of beams not provided already. For instance, a student may want many narrow beams close together and could make his own mask to accomplish this effect.

8

Mirrors and Supports

There are 24 metal mirrors in the *Kit*. They are unbreakable but do become scratched. They have supports so that they can be set on the floor in a vertical position.

Screens

Folding cardboard screens which stand up by themselves are used throughout the work as surfaces upon which to project light and shadows.

Probes

Each pupil should have one or two pieces of ⅛-inch dowel, 12 inches long, to use as a probe. The rather narrow stick can be poked into the beams to cast thin shadows which are interesting and useful.

Containers

Clear plastic cylindrical containers of three sizes and with different types of lids are used in Section VII. When filled with water, these containers bend the light beams and cause some interesting color effects.

Sugar

Sugar mixed into the water in the plastic containers changes the way light passes through the containers. You will need to supply your own sugar, as well as spoons and cups for handling it. (You may substitute salt for sugar.)

Combs

Black plastic combs are useful for turning wide beams into narrow ones quickly and easily. Their use is described in Section VII.

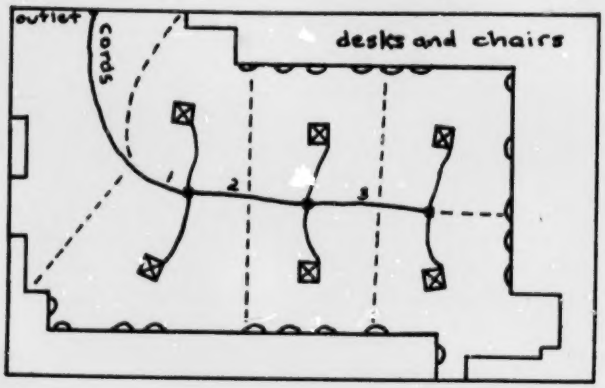
Extension Cord

In the next section you will find a description of a way to set up your classroom. The heavy-duty extension cords provide three plugs each for the light sources. You can connect the cords together to achieve the best arrangement for your particular classroom. Having all sources plugged into one cord is convenient, since you can pull the extension cord plug and turn off all sources in order to get the class to come together for discussion or other purposes.

Tape

A roll of masking tape is provided so that cords may be taped down for convenience and safety.

SETTING UP THE CLASSROOM



Setting up the classroom for OPTICS each day will not take too much time after you have done it once or twice. First, all desks and chairs must be pushed to the edges of the room, so that a large amount of floor space is cleared.* This space should then be subdivided into six smaller work spaces. A light source will be placed in the center of each of these. You can then place the extension cords on the floor, keeping two things in mind. First, all the sources will have to be plugged into the cords at one or another of the outlets, and second, the extension cords themselves should intrude into the six working spaces as little as possible. The diagram shows a top view of one possible arrangement.

It shows six light sources (marked by X), work areas around each source, and three joined cords threaded through the room so that they do not interfere too much with the open space around any source.

** If your desks are not movable, you will probably have to borrow the gym, auditorium, or other open space for this unit. You should be able to darken the area, and you will need an electrical outlet.*

Once the sources and extension cords are in place, and the sources are plugged in, it is a good idea to tape the wires down to the floor. The cord from each light source should be taped down fairly near the source, and the extension cord taped down here and there. This will keep everything in place, even if students kick some of the cords as they move about the classroom. Some days you will also need to tape down the sources.

Student helpers can distribute the other smaller equipment needed for the day's work, either by passing it out to the students or by putting an appropriate amount of it in each work area near the source.

The classroom should be darkened by lowering blackout curtains and closing blinds or shades. Then, with the lights off, it will be sufficiently dark to make the light beams from the sources vivid and clear. If you cannot darken your windows, then perhaps you can make arrangements to switch rooms for the OPTICS hours. One teacher used the auditorium stage for her work. The room must be particularly dark for the work with colored light. Some classes have successfully gone through much of the work without blackout curtains, but the darker the room is, the better.

Some teachers have left one source and a small collection of the other equipment permanently available on a table in the classroom for the use of students working independently during free hours.

Precautions

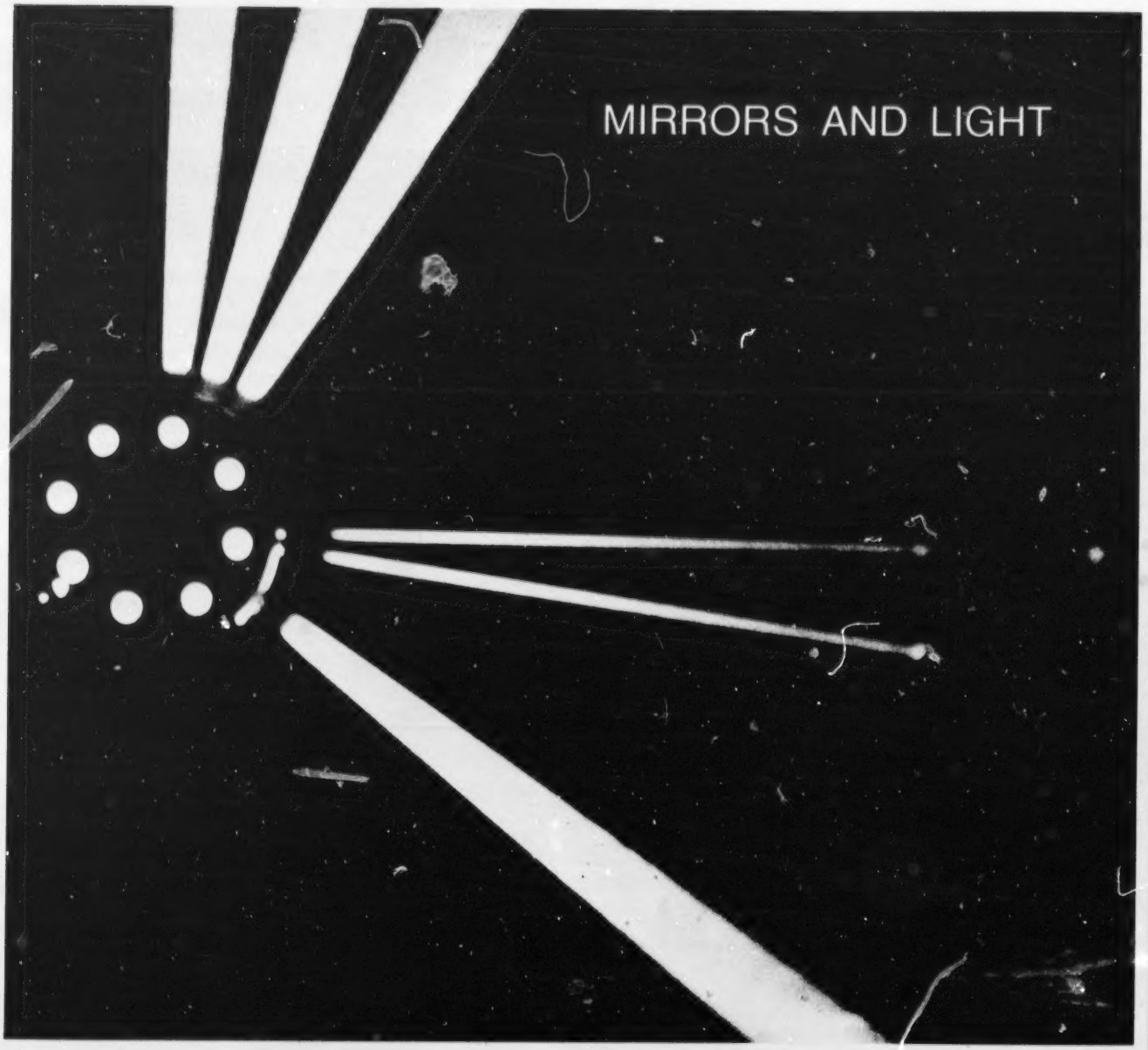
When all six of the sources are plugged into a single outlet, they are drawing approximately ten amperes, which is a considerable amount of electric current. If you find that you repeatedly blow fuses, then the particular circuit into which you are plugging the cord is either inadequate or temporarily overburdened because it is simultaneously furnishing current for some other

purpose. For instance, one teacher found that she blew a fuse if she turned on her regular classroom lights and the sources at the same time. If you have any problems of this type, you should work them out with your janitor or building superintendent. He may suggest using two or more extension cords on separate outlets.

The bulbs in the sources are protected by the cardboard holder. In trial teaching, no bulb in these sources has ever broken, but if, for any reason, one does break, unplug the source immediately, and then put in a new bulb.

Water is used in the last section of the unit. If it were spilled on the bulb, the bulb would certainly break. It is unlikely that this will occur, but if it should, unplug the source or sources immediately, replace the bulb, clean up the water, and you're ready to go again. Paper towels should be handy near each source during the parts of the unit calling for water-filled containers.

The bulbs in the sources get very hot and may possibly damage the surface on which the source rests. Normal wood or asphalt-tile floors should not be noticeably affected. If the top of the source comes loose, the bulb can drop down closer to the floor and can cause even asphalt tile to bubble. Mend any source whose top has given way, before continuing to use it.


MIRRORS AND LIGHT

Time: One or two sessions

Equipment: Sources, #1 masks. For each student: at least two mirrors, a screen, and a probe stick.

For the initial activities, and before the first session, you should insert four masks into each source so that one wide and two narrow beams shine out from each hole. Be sure that no colored-beam masks are at hand at this stage.

If you have additional mirrors, they should be made available, as the activities develop, to students who need them.

Introduction

The following activities involving mirrors and white light beams are suggested as a beginning. With a minimum of introduction, the students begin freely to explore and observe aspects of reflection and some of the properties of shadows. These preliminary activities can occupy one or two days, or even longer. When you feel the students have gotten all they can out of this fairly undirected activity, you can introduce them to the more systematic work described in the next section.

Getting Started

When the students are ready to divide up into groups and begin working at the light sources, plug in the main extension cord, and check that all the switches on the light sources are turned on. At this point, you shouldn't have to say very much to get the children started. If you give them too precise a direction too early, it will probably stifle, rather than stimulate, their investigations. In trial classes, most students have immediately begun to place the mirrors in the beam paths and have tried to bounce the light from mirror to mirror. The light patterns on the ceiling are also interesting.

If someone needs a starting point, you can suggest something general like this:

See what you can do to the light with your mirrors.

See if you can find several different ways of shining a beam on your screen by using your mirrors.

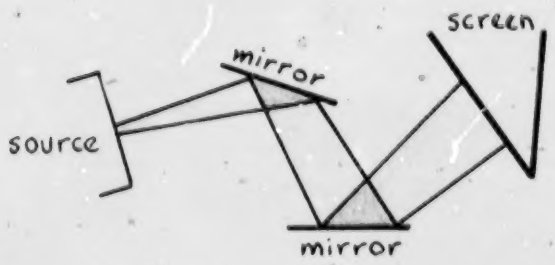
What kinds of patterns can you make, using your mirrors on the light beams?

The probe sticks will cast shadows if they are held in a beam of light. Some of the students will come to this on their own. To help others who need direction or want to know what the sticks are for, you can ask questions:

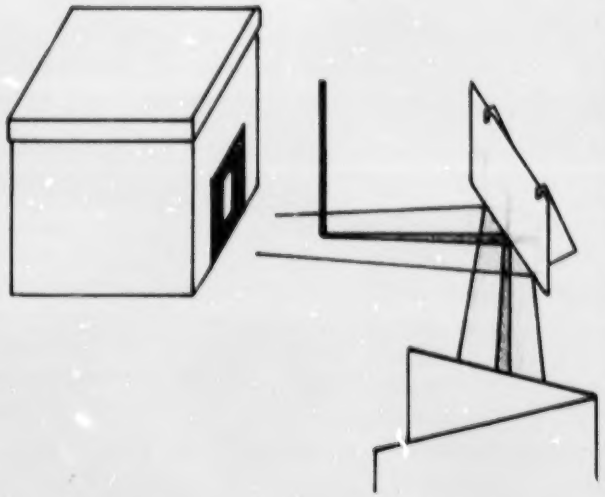
What kinds of shadows can you form, using your probe stick and the mirrors?

Can you project a shadow on your screen with your mirrors?

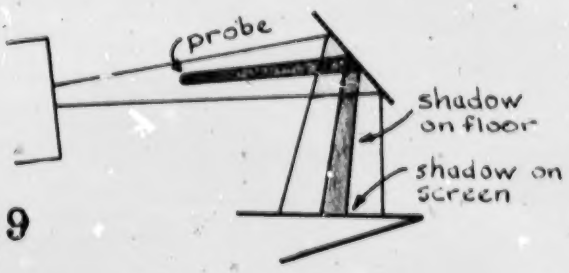
Throughout this *Guide*, sketches will be used to help describe the activities of the unit. Usually the sketches will show equipment arrangements as they would look from above. For instance, here is one arrangement. The bold lines are the tops of mirrors and a screen. A wide light beam is going first to one mirror, then to another mirror, then onto a screen.



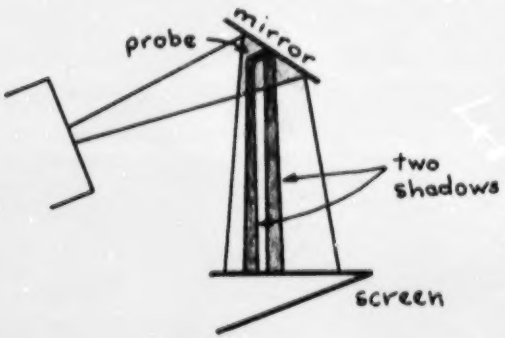
A probe stick held vertically in a beam of light in front of a mirror screen arrangement like this –



. . . would be shown like this in a top-view sketch:

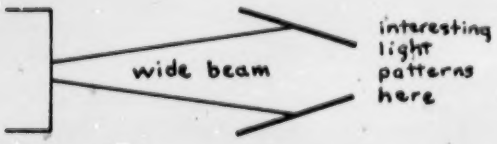


One of the simplest of the many multiple-shadow effects which are possible might be shown this way:

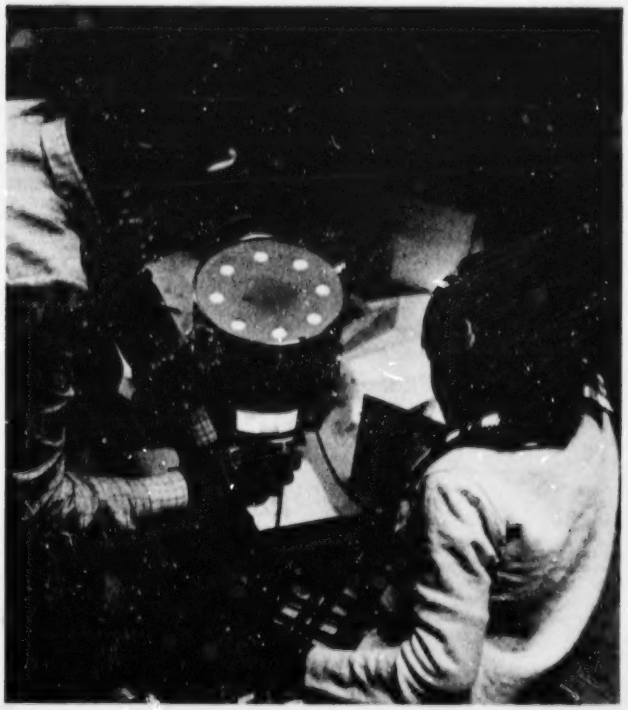


Students will find that they can make a probe cast two, four, and even more shadows, all at once.

Your students will probably try these and many other things. For example, here is one interesting arrangement made by a student. He placed two mirrors like this:



He then moved the mirrors around a little bit to produce interesting patterns.



Some may try to "pass the light" all around the source using all the mirrors available. The beam gets rather dim after many reflections (you might ask the students to think about why this is true, when they run up against it), and they will probably struggle on with a light beam they can hardly see.

You can help the students share their ideas and can ask stimulating questions of those students who need help in using the materials. For example:

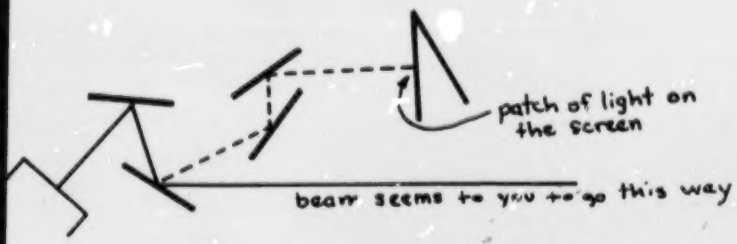
Can you get your probe stick to cast four shadows?

Can you split one beam into many beams with your mirrors? How many?

Can you combine two beams into one?

Systematic Tests

Even early in the unit, opportunities will arise which you can use to help the students begin to look carefully and critically at their own work. In any situation in which the pathway of the light is not completely obvious to the students or to you, there is a chance for you to help the students develop tests to see exactly where the light is going. For example, suppose, as you are walking around the room and looking at the students' work, a pair of them call you over and say something like, "We used four mirrors, and the light bounces from one to the next and then hits the screen." You look down and see this:



The students see a patch of light and think that a light beam has traveled to the screen. To you, it may look as though their beam is shooting off along the solid line and missing the screen completely, while the patch on the screen might be made by some other beam entirely. You can ask the students questions like these:

Are you sure that your light beam is doing what you say?

Can you find a way to prove to me that the light shining on your screen has really bounced off all those mirrors?

How can you be sure that light patch isn't coming from somewhere else?

These kinds of questions may be enough to get the students to try some simple tests, such as the following two:

1. They can wiggle any of the mirrors slightly. If the patch on the screen does come from a beam that has hit the mirror, it should also wiggle.

2. They can put a probe or pencil in front of the various mirrors in the arrangement and look for shadows on the screen. If a probe is put in anywhere along the true path, it will stop some of the beam and cause a shadow on the screen. If the probe is moved back and forth, a shadow will be seen moving back and forth on the screen.

If the students do not respond to your questions by inventing tests like these, you can ask them questions which are more direct:

If your beam does bounce off this mirror, what will happen to the patch when I move the mirror?

What will we see if you put your probe in front of this mirror?

If a student has a complicated setup of beams and mirrors, and the beam does seem to you to be following the complicated path he has indicated, you can still ask questions that will help him design his own testing procedures:

Can you find a way to prove that the path of light on your screen isn't coming from somewhere else?

II. MIRRORS AND LIGHT: PUZZLES AND PROBLEMS

Time: One or two sessions

Equipment: Sources, #2 masks. For each student: at least two mirrors, a screen, and a probe stick.

After the classroom is set up, each source (as well as the cords) should be fastened to the floor with a couple of short pieces of tape.

Introduction

Here is a sequence of puzzles and problems that call for students to apply their observations of the behavior of light. Some of these problems can be tackled by everyone in the class, while others are best offered to individual students who are ready for a special challenge. You can plan

on one or two periods for this work, but you may want to allow more time. You will have more insight into the children's problems if you try these puzzles on your own before giving them to the students.

Hit-the-Target Problem

First, tell the pupils to mark on the floor where one of their narrow beams is. (If the second beam is distracting, it can be blocked off with a mirror or dark paper.) They can do this by actually drawing or taping a line on the floor or by laying a probe stick or pencil on the beam. Turn off the sources by pulling the extension cord plug (or plugs if you are using more than one outlet). Now, ask a question like this one:

Can you set up your equipment so that after I turn the sources back on, your light beam will hit one mirror, bounce to the second mirror, and from there bounce to the screen?

In order to solve this problem, the pupils will have to begin to make definite predictions about the directions in which light travels after hitting a mirror. Most pupils, after the exploratory period, will have a pretty good idea about how the incoming beam directions are related to the mirror position. A few won't, and they will need quite a bit of help. The best way to help them is to break the overall challenge into a sequence of smaller tasks which can be analyzed one by one:

Where should you put your first mirror? . . . Where do you think the light will go after it hits that mirror? . . . Okay, now, where should the second mirror be put?

After sufficient time has elapsed, turn the sources back on, so that the pupils can see if they have succeeded. Many will have missed and can now correct the flaws in their set-ups. The entire problem can be repeated, and those who succeeded the first time should be encouraged to try a different way or to put their mirrors much farther apart. The greater the distance between the mirrors, the harder it is to get the beam to go where you want it to go.

While the quicker students are waiting for their light source to be turned back on, they can check one another's arrangements and see if they think these will work. You may want to challenge some of these students to find ways to prove that their arrangements are going to work.

After the first or second run of this problem, it will probably be best to let the students turn their sources or beams on and off individually. They can use the source switch, if everyone in the group agrees, or they can simply use an object like an extra screen or mirror to block off a particular beam. Of course, you always have the extension cord plug available if you want to get the class together.

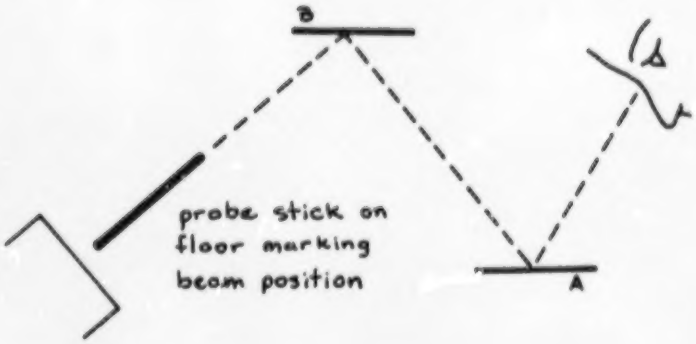
You can make the challenge harder by choosing a *specific spot* on the screen as the target:

Make a mark on the screen. Can you set up your mirrors so that the light beam will hit right on the mark?

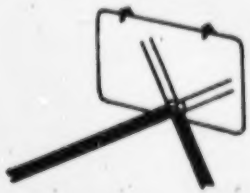
Visual Techniques

In trying to get their mirrors set up perfectly so that the beam will, in fact, hit the target, some of the pupils may discover that they need not rely on guesswork at all. Even with the sources off, you can look in the mirrors and see how the beam is going to behave by, for instance, putting your eye where you want the beam to arrive in the end and looking back at the last mirror.

If the arrangement of the mirrors is accurate, in mirror A you will see mirror B, and in B you will see the end view of the probe stick which you used to mark the beam position.



Some students try to use pencils and sticks to get their mirrors lined up. They have laid sticks in front of a mirror like this:



By looking at the "X" formed by the sticks and their reflections, they could tell if light coming in along one of the sticks would go out along the other.

If some students have discovered techniques such as these, give them time and opportunity to explain them to other students who have not. If no one has invented these or other methods to get a perfect setup, you can challenge the class to find one:

Can anyone find a way to check his setup and make it perfect before the sources are turned on?

Can you check your setup by looking in the mirrors?

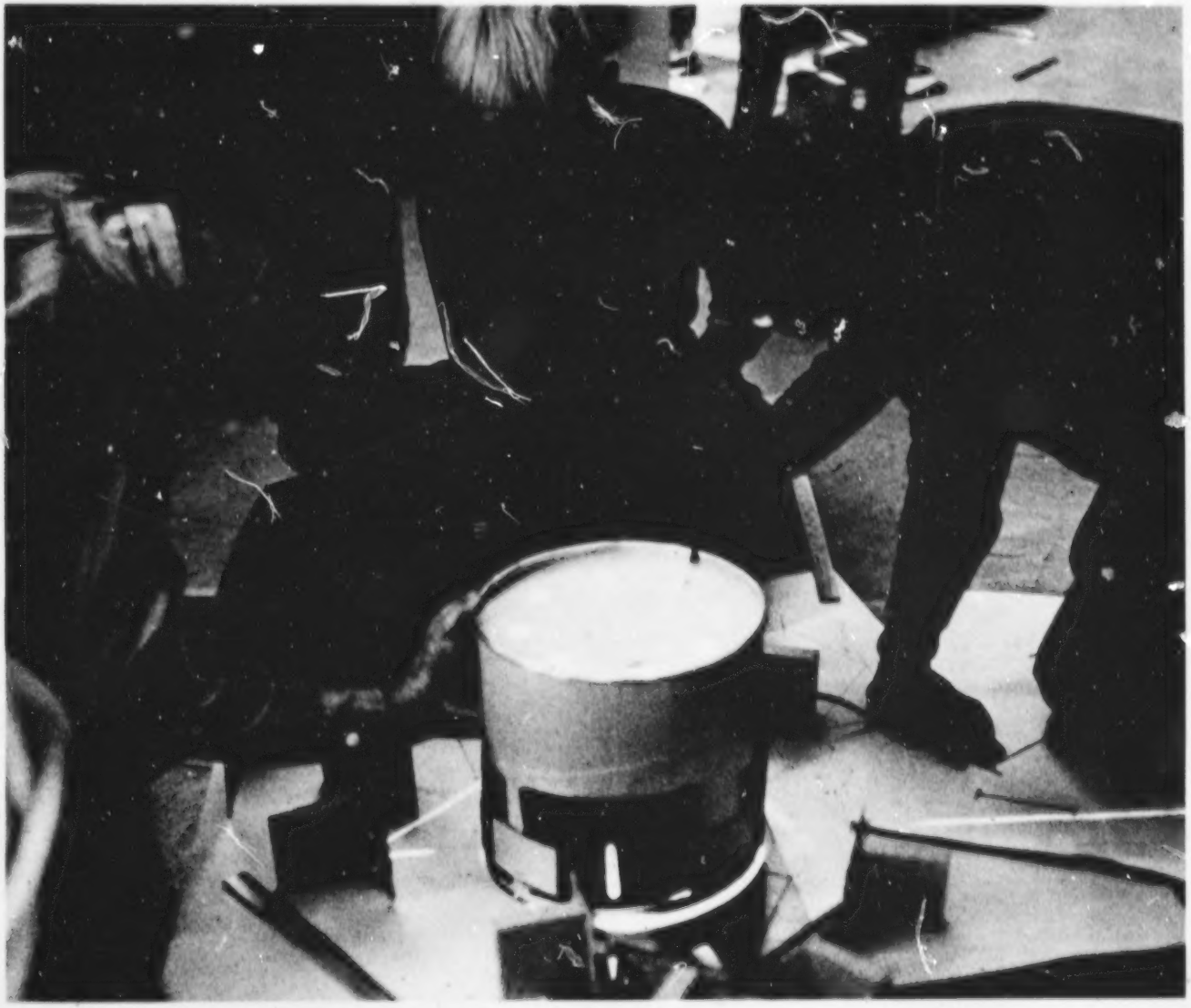
Can you test your setup by tracing out exactly where you think the light will go?

The entire class can then try these techniques and make arrangements that will let the beam hit the target when the source is turned back on. It is useful to have the students who do not grasp these techniques look in the mirrors and then look at the "X" patterns *with the sources on*. That is, with the beam on, a student can move the screen aside and put his head in its place. If his eye is in the right spot, he can look back into the last mirror and see the entire beam, all the way back to the source, as a straight line of light. Likewise, the beam itself makes an "X" pattern at a mirror. These observations may help a student see the relevance of the visual techniques for getting the mirrors lined up with the beam off.

The first puzzle will undoubtedly have to be repeated quite a few times before all, or most, of your students can solve it with some understanding and predictability. Some of your quicker students may, therefore, want to work on related problems. For these students, you can pose more difficult problems:

Can you set up your mirrors so that two different beams will hit the screen at exactly the same place when you turn them back on? Can you do this with more than two mirrors?

Can you set up your mirrors so that two or three beams will cross exactly at a particular place on the floor when you turn your source back on?



Time: Two or more sessions

Equipment: For these activities, drawing materials are necessary, in addition to the equipment mentioned at the beginning of Section II (sources, #2 masks, mirrors, probes, and screens). Pencils, rulers or other straight edges, and large and small drawing paper (such as newsprint) are needed.

Introduction

The following activities invoive the students in drawing maps and plans for patterns of light that they can then form by using their mirrors and a narrow beam. They may also make detailed drawings of just how they see the light bounce off a mirror as they experiment with the equipment.

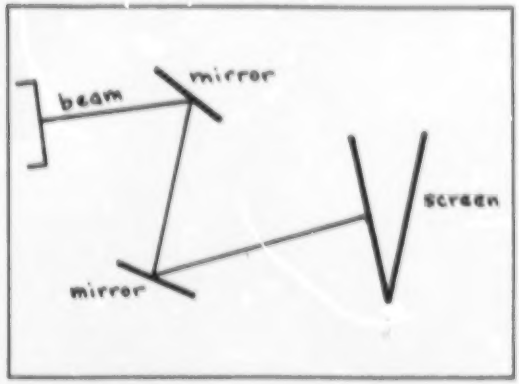
During most of this work there will be some students testing their plans at the light sources and some students drawing. A number of teachers with large classes have taken advantage of this by providing space to draw at the desks pushed to the side of the room, thus leaving extra space around the sources free for work with the light.

Large Plans

The most useful type of plan to start with is one that is full size. The student can check his plan on the floor, with the mirrors, screen, etc. placed right on the paper in the indicated positions. If the plan works, the light beam from the source should shine along the lines drawn for it.

Tell the students that they will be testing their plans this way when they are finished. They need not draw mirrors, just lines to show where the mirrors will stand. Some students will draw several plans in the time that the rest manage one. The students should have their mirrors while they are drawing, in case they want to put them on the plan as they go along to help them visualize their arrangements. Emphasize that their plans should be full-size pictures of where the beam is actually going to go.

A student might end up with a plan like this:



When enough students are ready, they should turn the sources on and try out their plans.

Most plans won't work. Some questions you can ask that may help the students recognize errors are these:

Can you turn your mirrors so that the beam does follow the path you drew for it?

Can you draw your lines again so that your plan will work?

Many students will probably want to try again from the beginning with the sources off. If their first plan worked pretty well, they may want to try a more intricate one. They can share mirrors for trying out plans, if they need more than their normal supply for a really complicated situation.

Small Plans

At some time during this work, when you feel the students would benefit from a new line of attack, you can start them off making smaller plans. The sources should be turned off and the students each given several sheets of paper ($8\frac{1}{2}$" × 11" is fine).

Draw a straight line for your mirror and another straight line for a beam of light coming in and hitting the mirror, like this—

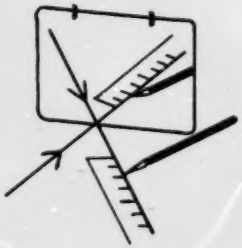
(You can draw an example on the board or a sample piece of paper.)

Now see if you can find a way to draw another line to show exactly where the beam will shine when it bounces off the mirror.

Each student can do several of these, not all the same. For example, he might begin with the following problems on separate sheets of paper:

Some teachers put these problems on ditto sheets ahead of time and gave each student his own copies.

Techniques based on looking in the mirrors can be used to complete the little plans accurately. For instance, by putting a mirror on the mirror line of such a plan, you can draw a line extending the reflection of the incoming beam line. This drawn line will be the path the reflected beam will take.



The lines and their reflections will form a perfect "X" if they are correctly drawn. This fact can be used directly to find where to draw the second line.

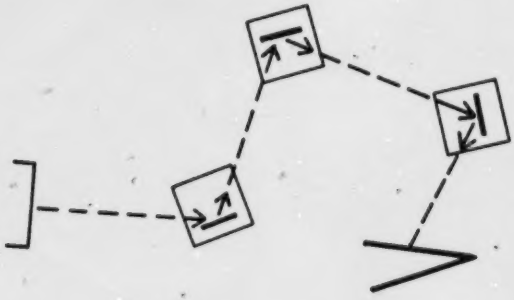
As these plans are completed, they can be checked with beams from the source. Also, the students should be encouraged to discuss and share what they have learned about drawing plans that work.

The same techniques can, of course, be used to make a large or complex plan, mirror by mirror. Some pupils may want to return to making plans on the larger scale.

Combining Small Plans

Another interesting thing to try is to combine several little plans to make up a large-scale arrangement involving several mirrors.

One possible arrangement could be like this:

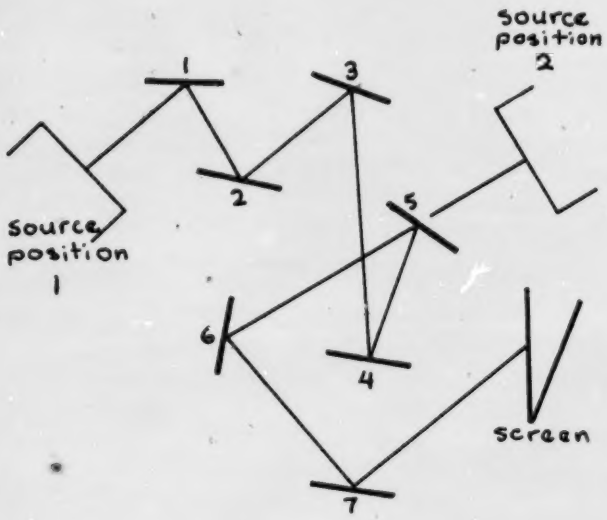


When they put mirrors on the mirror lines in the various plans, the light should follow the desired path. With the help of these little plans, otherwise difficult problems become simple. For instance, it is now easy to place the mirrors so that two beams will cross at any desired point when the sources are turned back on.

Elaborate Plans

Some pupils will want to collaborate on elaborate arrangements, utilizing many mirrors and enormous full-scale plans. Many sheets of paper can be taped together for this purpose. Some frustration will arise if the arrangement becomes too extensive. After many reflections, the beams become very dim, in part because the mirrors absorb some of the light from the beams, in part because the original beam spreads out more and more.

These extra-large plans can still be thoroughly tested with light beams – but only part by part. If the beam is too dim after four reflections, then the light source of the plan can be repositioned to start the beam over again after the fourth mirror, so as to test the remaining part of the plan. For example, if this is the plan –



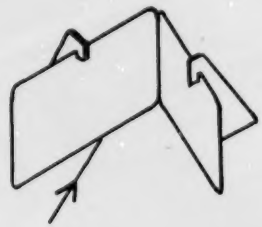
the fifth mirror can be removed and the plan turned so that the beam shines in as shown to test the last part of the pattern. It is easier to move the plan than the source if several students are working at one source. Also, you can test the last part of the plan *backwards* by removing the screen and shining the beam in along the path from that end.

Individual Variations

There will probably be students who want to go slowly or who don't catch on to some of these activities, and some who move through the activities quickly and want to go on to new challenges.

If a student does not yet make the connection between what he sees with the sources off and what the light beam actually does, you can suggest that he trace out the patterns with the source on. With several mirrors placed on a large sheet of paper and a beam bouncing from mirror to mirror, the positions of the mirrors and the beam can be traced. The way the tracing lines look in the mirrors as they are drawn with the beam on may be interesting and enlightening to the student.

To those students who, on the other hand, need more difficult problems to solve, you can offer more complex plans to complete. For instance, you might put two mirrors down on a piece of paper like this and draw lines and an incoming beam line:



Can you figure out what the path of this light beam will be? Can you draw the path?

Here is another such arrangement:

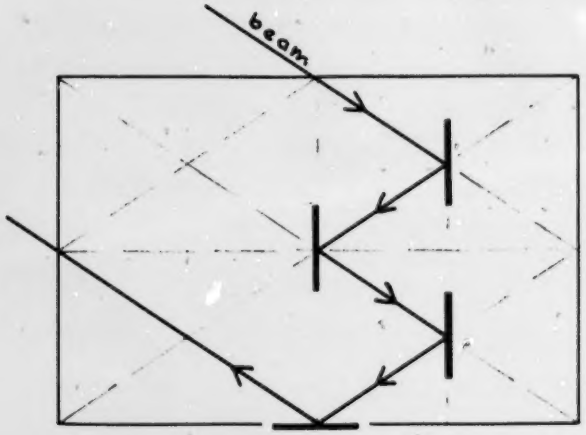
When they think they have solved these problems, the students can try out their solutions with a beam. There is a great variety of such problems, and students can make them up for one another to solve.

Paper Folding

Another type of problem that is related to the making of plans can be put with the following question:

Can you fold a piece of paper so that, when you unfold it and lay it flat, the creases form a plan – that is, if you put mirrors on some creases, the light beam will follow other creases?

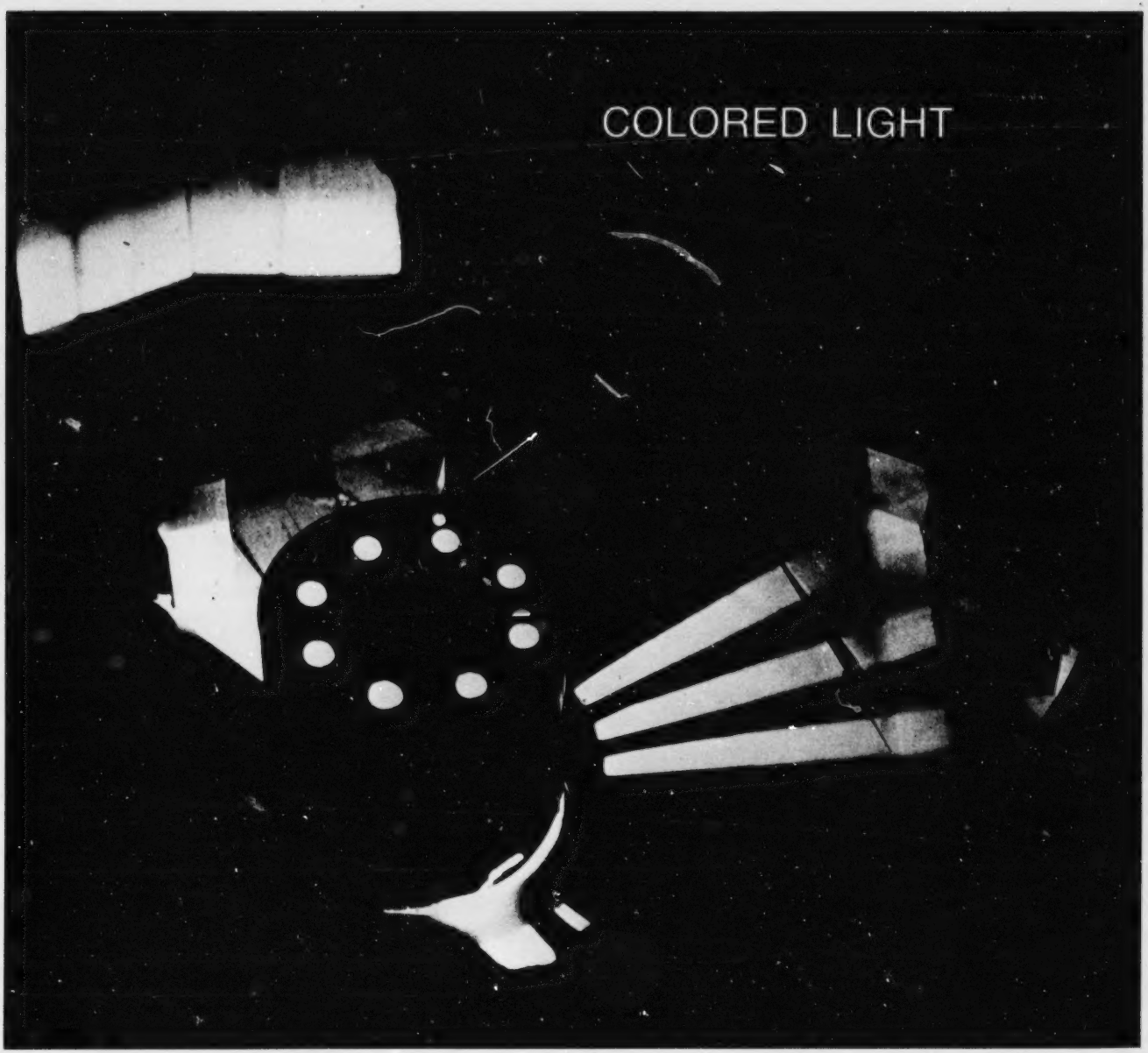
By carefully planning the folds or by using trial and error, you can crease a piece of paper in a variety of ways to form a plan. The following is one example.



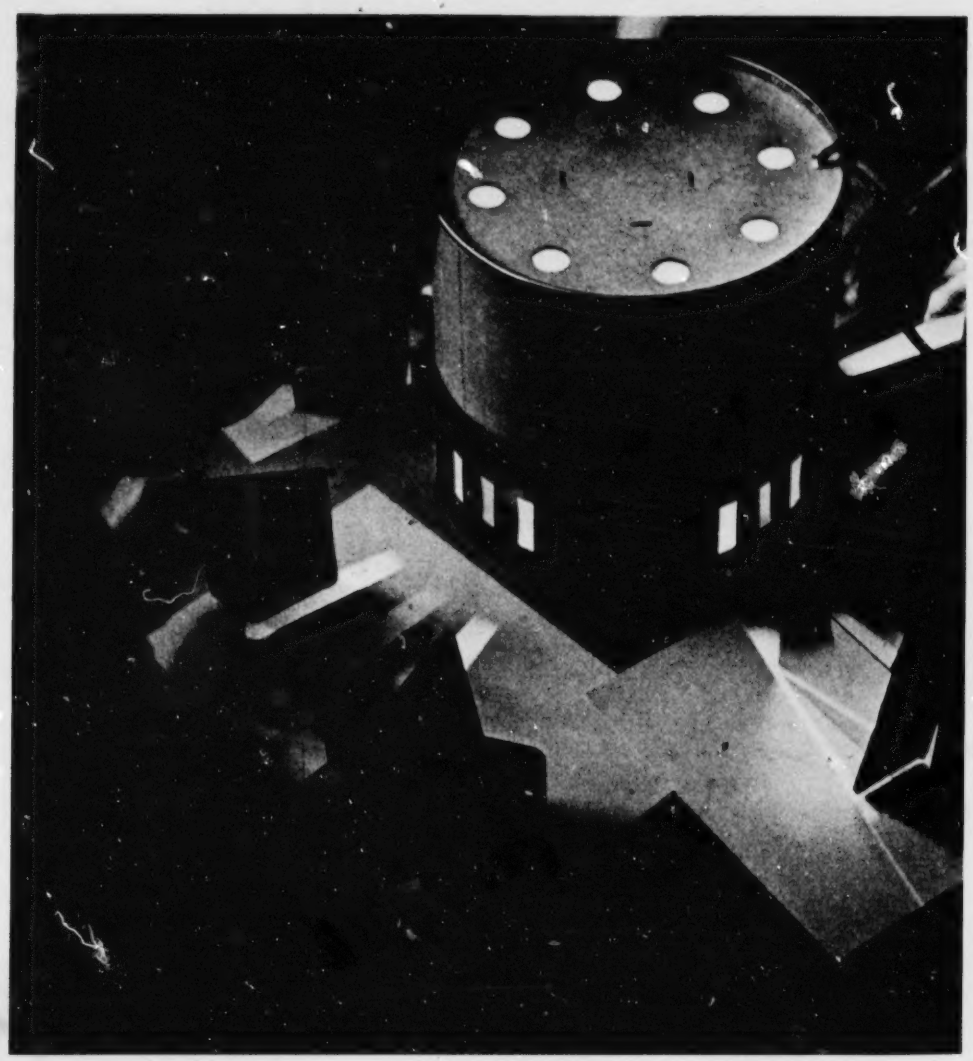
If mirrors are laid on some of the creases, then the light will follow along other creases.

Designs

Another activity which has interested some students involves designs. A student can make a design pattern of lines and then work out a way to make the design out of light beams, using mirrors. Problems will arise, since in complicated designs one mirror may get in the way of another and since, after many reflections, the beam gets dim. Getting around these difficulties can be an interesting part of the activity.


COLORED LIGHT

IV. COLORED LIGHT: COLORED LIGHT MIXING



Time: At least two sessions, and maybe more

Equipment: Sources, #3 masks. For each student: two mirrors, a probe stick, and a screen. Some white paper (8½" × 11") is also needed. The room should be as dark as possible for these activities.

Introduction

Each of the four openings on each light source should be covered with the #3 mask, containing the three narrow pieces of colored plastic. These plastics, each about ½" wide, will filter the white light coming from the bulb and thereby create three beams colored red, blue, and green. These three colors can serve as "primary" colors (in the sense that by mixing them we should be able to span the entire range of the colors we know).*

Again, each student should have at least two mirrors. As produced by the source, the three beams head off in different directions. In order to make them cross and mix together on the screen or floor, a student will have to reflect the beams back toward one another.

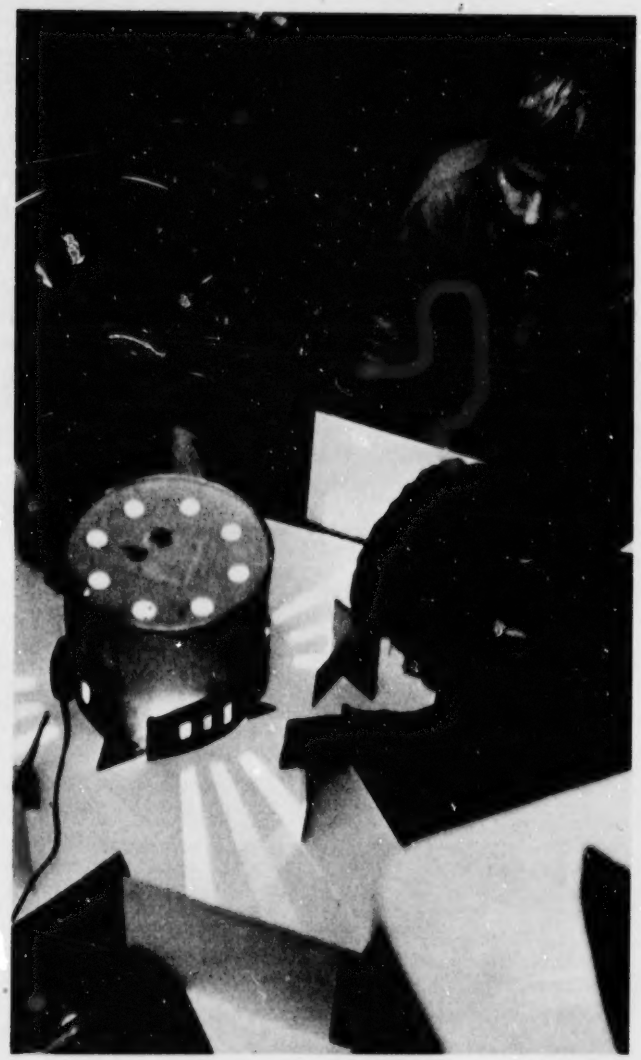
In addition to the screen, white paper should be given to the students. The beautiful colors where the beams cross will occur on the floor as well as on the screen, and a sheet of white paper on the floor will show them up more brilliantly than the floor itself will.

Beginning Activities

Once the sources are set up and masked and the other supplies have been passed out, the students are ready to begin to manipulate the colored beams of light freely.

Probably no starting instructions of any sort will be required, but you can start things off with a few simple suggestions if necessary.

* *See Appendix for further background.*



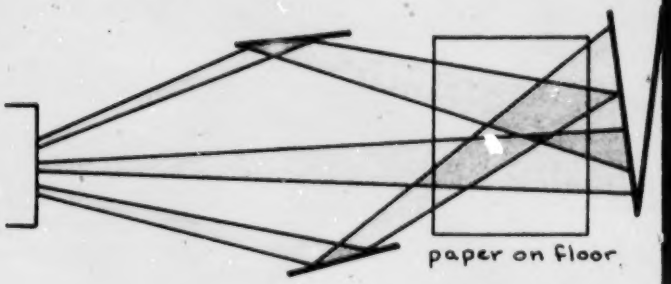
You can use your mirrors to mix these beams together.

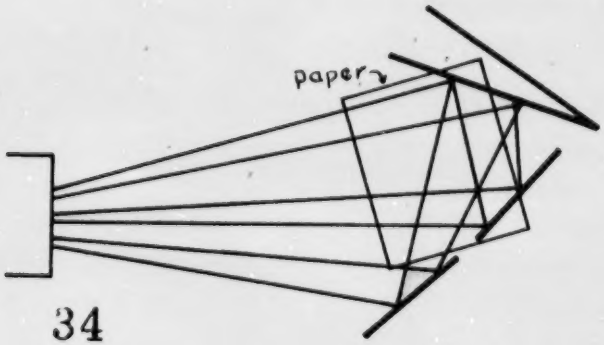
See what colors you can make on your screens by shining the beams together, like these.

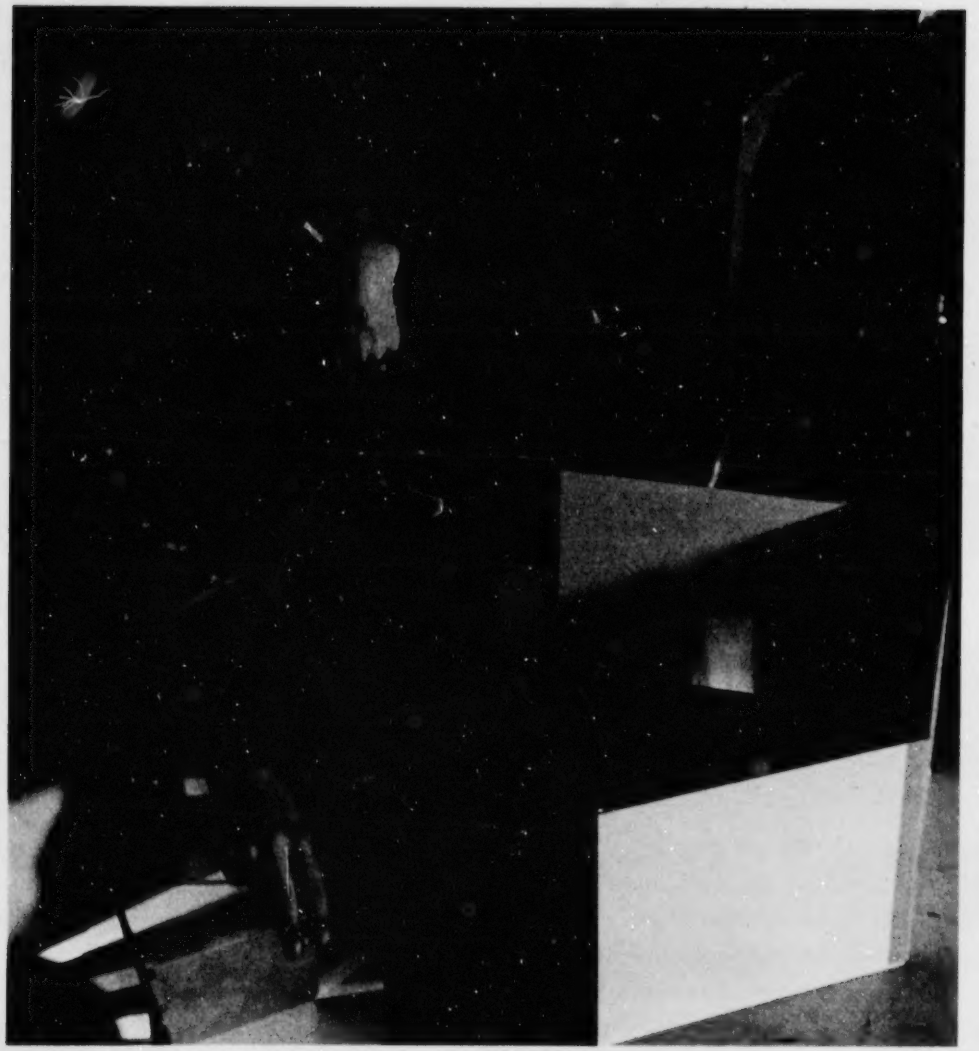
You can put the white paper on the floor to see the colors better.

The students will probably become interested immediately and will carry on for themselves.

Here are two typical arrangements of sources, mirrors, and screens or paper, showing color mixing:







Your students will design their own, equally effective arrangements.

It is probably best to let the exploration of these colored beams go on for a considerable time, with no attempt to organize or record the variety of effects that will be observed.

After a while you may want your class to do some analysis of color mixing. In a trial class, one student organized his findings by filling in a table he made:

	red	blue	green
red			
blue			
green			

He filled in each square by mixing the two beams for that square.

This simple table has limitations, since when the red and green beams are mixed, the resulting color varies, depending on the precise way in which the mixing is done.*

Ranges of Colors

When the students have had plenty of experience mixing color, you can say to the entire class, or to small groups –

Did you notice that you can get more than one color or even a range of colors from two beams?

One way to get a large range of color is to rotate the screen.

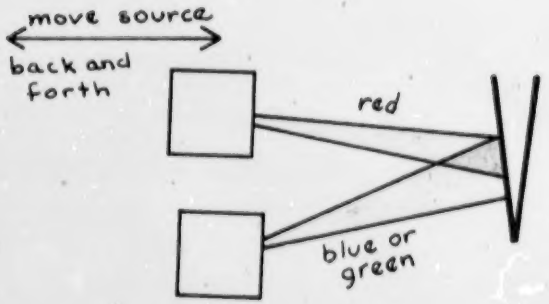
* *See Appendix for background material on ranges of color.*

When you have two beams (any two colors) mixed on the screen, try turning your screen slowly and see what happens to the colors. Turn it so that the colors still mix on it.

Students may experiment with turning the screen while all three beams are shining on it, as well as pairs of beams.

If you would like a way to help your students understand why these procedures are providing such a wide range of colors, you can demonstrate a different method to vary the colors. Have the class gather in such a way that they can all see a screen. Arrange two light sources so that a green or blue beam from one and a red beam from the other both fall on the screen where they can be mixed.

Now, one or both of the sources can be moved closer to and further from the screen. This will change the relative intensity of the two beams and will, thereby, change the color seen on the screen. When the students rotate their screens, they are achieving the same sort of intensity variation but in a slightly different way. It would be good if the students could try out the two-source experiments for themselves. If space limitations make this impractical, your carrying it out as a demonstration will serve a useful purpose.

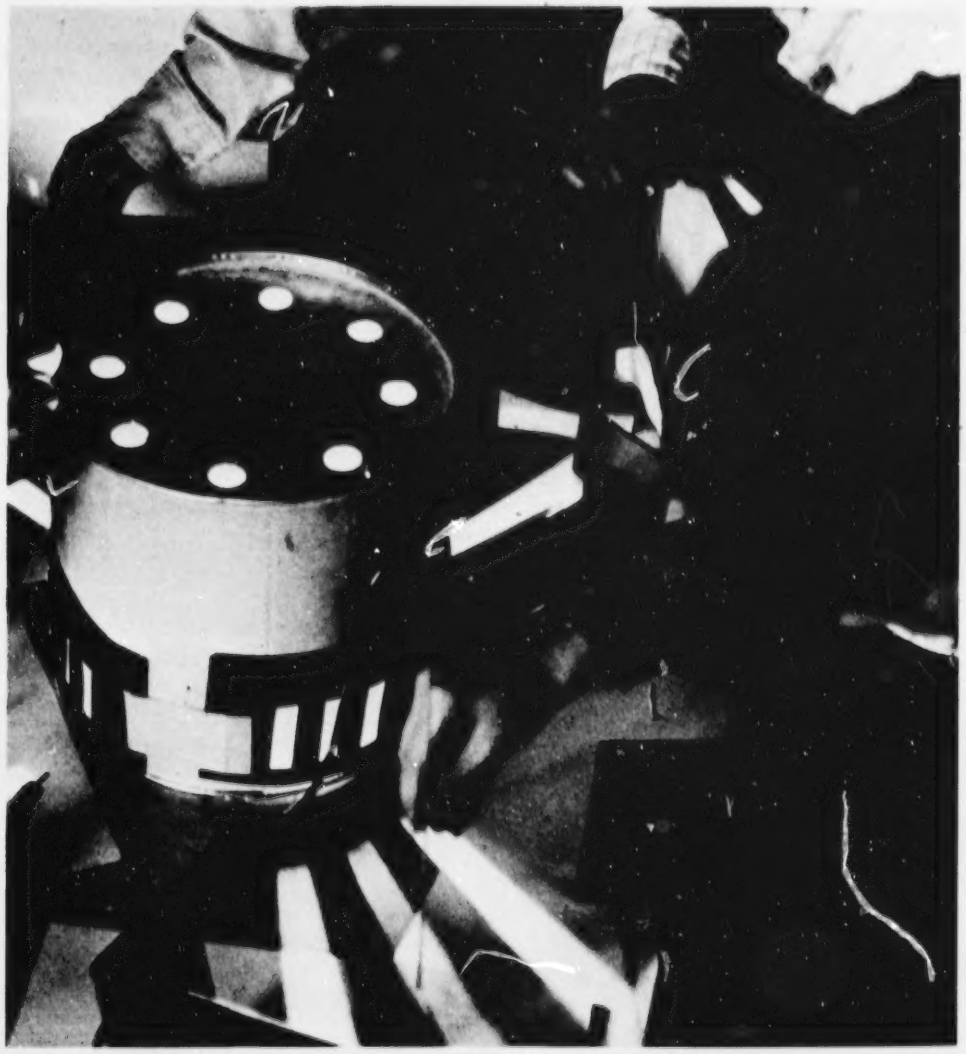


You may suggest at some time that it is interesting to use screens that aren't flat, and the students may like to find objects around the room to look at in the colored beams.

Folded or crumpled white paper will provide a variety of colored regions, and students can also prepare paper objects to look at in the beams.

If time permits, you should work out the possible color variations on your own. If not, work along with a group of students.

V. COLORED LIGHT: COLORED SHADOWS

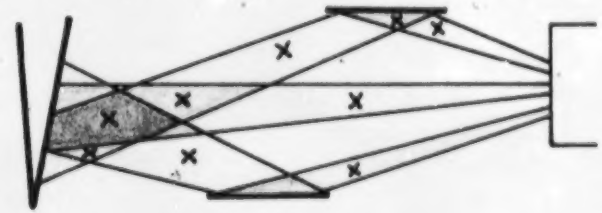


Time: One or two sessions

Equipment: Same as for Section IV

Introduction

While they are mixing colored light, some of your students will probably discover colored shadows. If necessary, you can introduce this phenomenon yourself or, at least, can help its discovery spread around the class. If no one discovers colored shadows, it is probably best to wait until quite a bit of time has been spent with the colored beams before you introduce this work.



A probe stick put in the beams at points such as those marked "X" will produce colored shadows on the screen and floor. You can simply ask the students—

What happens if you stick a probe into one of the beams shining on your screen?

The colored shadows are appearing because the probe stick is selectively stopping one or more of the colored beams. The light around the stick is left to hit the screen, producing colors just as it did when the stick was not there. The probe stick is acting like a very selective switch. A shadow, in fact, can always be looked at as the result of a switch effect. An object casting a shadow is

just a switch that doesn't turn off the light all over but does turn it off in some places. Those places are in the shadow. This, then, explains how the colored shadows arise. You see a shadow because some light is stopped by the stick, and yet, since other colored light is illuminating the area in shadow, you do see a color in the shadow.

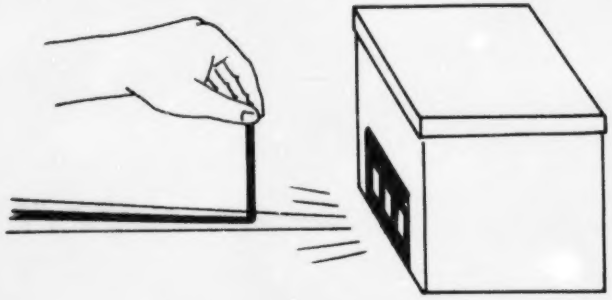
Free Activity

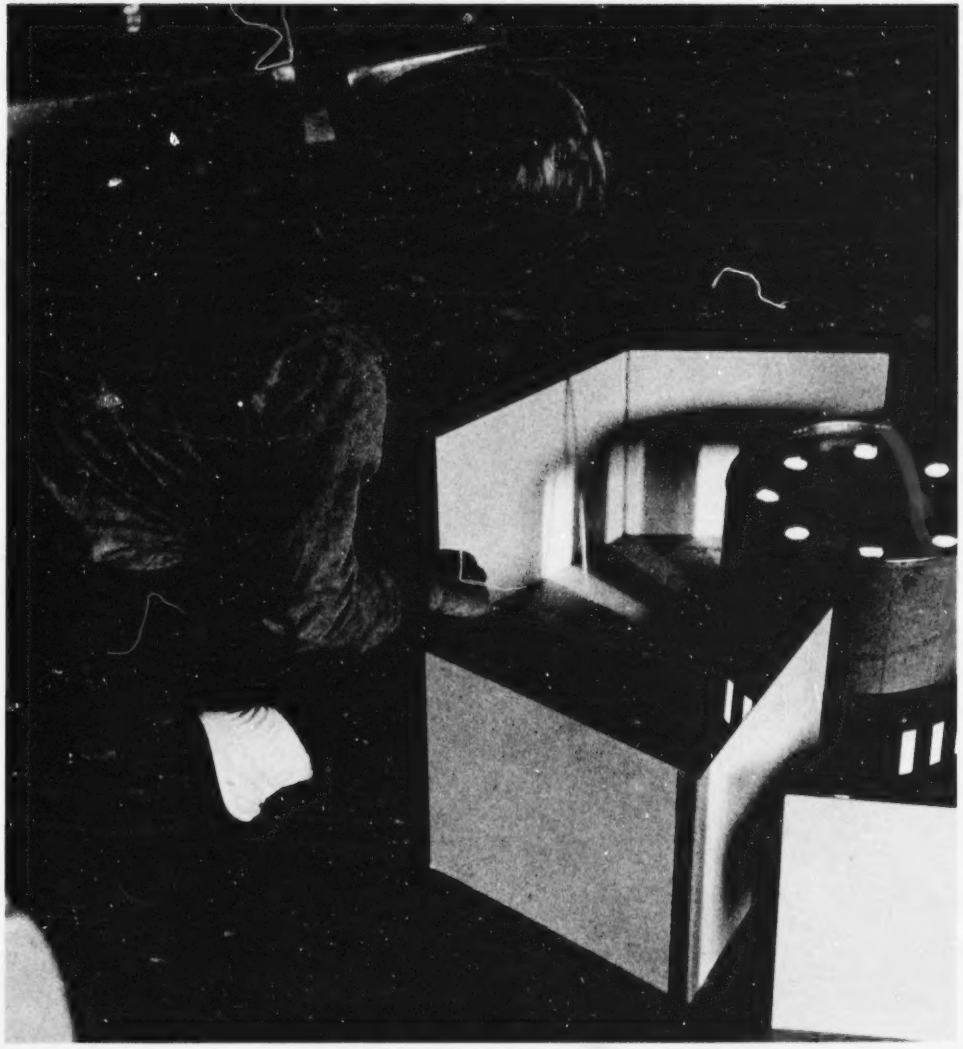
The students will profit if they are allowed time to experiment freely with colored shadows whenever they first encounter them. Such shadows may be noticed at any time in this work with color, since a finger poked into a light beam will frequently cause a colored shadow.

Colored-Shadow Puzzles

The following puzzles are fun and will help the students understand just where the colored shadows come from.

First, show the students which shadow you will be working with. It is the one you get when you simply hold a probe stick in a beam as shown here.

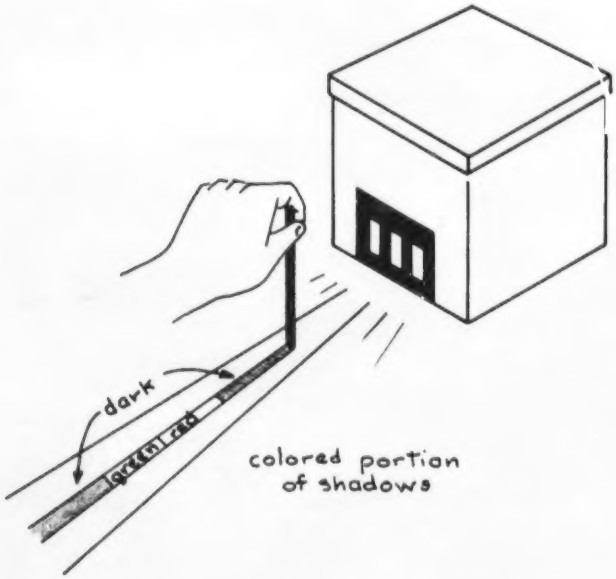




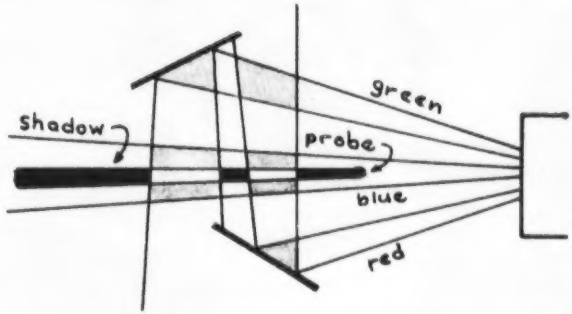
A good first puzzle to give the students, after they are at their sources and ready to go is this:

Make a shadow like the one I showed you; but make one part of it a red shadow, and, next to that make it green.

On the chalkboard you can sketch what you want. Your sketch should depict something like this:



After the students have been experimenting for some time, this type of solution will probably occur to some:



Each student should be allowed to solve this kind of puzzle at his own speed. Variations and complications can be given to individuals and groups who are ready for new challenges before their classmates.

An interesting series of puzzles to be solved consists of the following color sequence for the shadows:

PUZZLE	SHADOW
#1	black red green black
	↓
#2	black green red black
	↓
#3	black red yellow green black
	↓
#4	black yellow black
	↓
#5	black red blue black
	↓
#6	black red blue green black

Other series of puzzles may prove equally informative to the students who try them. A transition from one sequence to the next will require one or more shifts of equipment. Skipping a sequence may mean having to make more complicated changes to solve the next one.

White-Shadow Puzzle

After finding ways to solve puzzles like these, some students are intrigued with the problem of making a white shadow. There may not be enough interest to make this an activity for the entire class. For those students who are interested, it can be a very thought-provoking problem.

> How can a shadow be white? . . . It must have white light coming from it. . . . And yet some sort of light, white or colored, has to be stopped by the object casting the shadow. . . . Then how can it be a shadow in the first place? . . . The shadow exists because somehow you have blocked off some light which otherwise would illuminate the shadow region.

Put this together, and you can construct a white shadow.

There have been arguments among the students about whether or not a particular solution does give a shadow which looks white. Particular solutions to this puzzle or any of the others might serve as the core of a class discussion on the whole phenomenon of colored shadows and how one can predict what colors shadows will have in various situations.

One fascinating complication which has arisen for students making white shadows is that the color we see and name when we look at a part of the screen depends not only on the light coming from that part, but also on the light from the surrounding regions. A white patch of light on the screen will look slightly yellowish when surrounded by blue, and will look greenish-blue when surrounded by red.

In general, you can help simplify analysis of the colored shadows by reminding the students of the concept of the "switch." Any situation too complicated to analyze can be simplified by "switching off" individual beams—that is, blocking them with a ruler or strips of paper. As they are "turned back on," one by one, the complicated situation returns, step by step, and can be better understood. If a student sees a yellow shadow, you can say—

> *What will happen if I turn off or block out the red beam? What color will the shadow be then?*

Trying to predict these changes will sharpen the student's analysis of what he sees.

VI. COLORED LIGHT: PIGMENTS

Time: One or two sessions. Younger students usually want to spend more time on this than do older ones.

Equipment: Sources, #4 and #5 masks. For each student: lots of white paper and coloring materials. Mirrors do not play an important role here but should be available.

Introduction

With the equipment supplied in the *Kit*, you will find two types of masks (#4 and #5) designed to provide an opportunity to experiment with colored light and with paints, crayons, or colored paper at the same time. Mask #4 has all three colored plastics in it, each plastic being as wide as possible. This, when slid onto the source, provides wide, red, green, and blue beams right next to each other. Its main purpose is to color fairly large areas on the floor, so that a student can make quick comparisons of the effect of all three colors of light on drawings.

The other type, #5, is just the large pieces of colored plastic which, by themselves, can be slipped into the mask slot. The four mask slots of a source can be filled with these colored plastics, so that while the different colored beams are not right next to one another, wide beams of all three colors are available at each source.

The students should be provided with both of these mask types when the following work begins, so that they may choose and change their beams as they go along.

Pass out lots of white paper, along with coloring supplies with which the students are familiar. Colored pencils and chalk are probably not vivid enough to be exciting in this work. Poster paints and crayons work well. Colored paper can be made available for those who want it.

Just Drawing

To start things off, hand out the drawing or painting supplies and plenty of the masks needed for this work.

The students can work with their art materials on the floor around their sources. You can just say –

Make some small pictures, and see how they look when you hold them under the colored light.

This will probably get quite a bit of activity under way. In addition to looking at drawings in the colored light, the students can look through the colored plastic at drawings illuminated by white light.

The activities described below can be suggested to individual students or the whole class if they need ideas.

Double Drawings

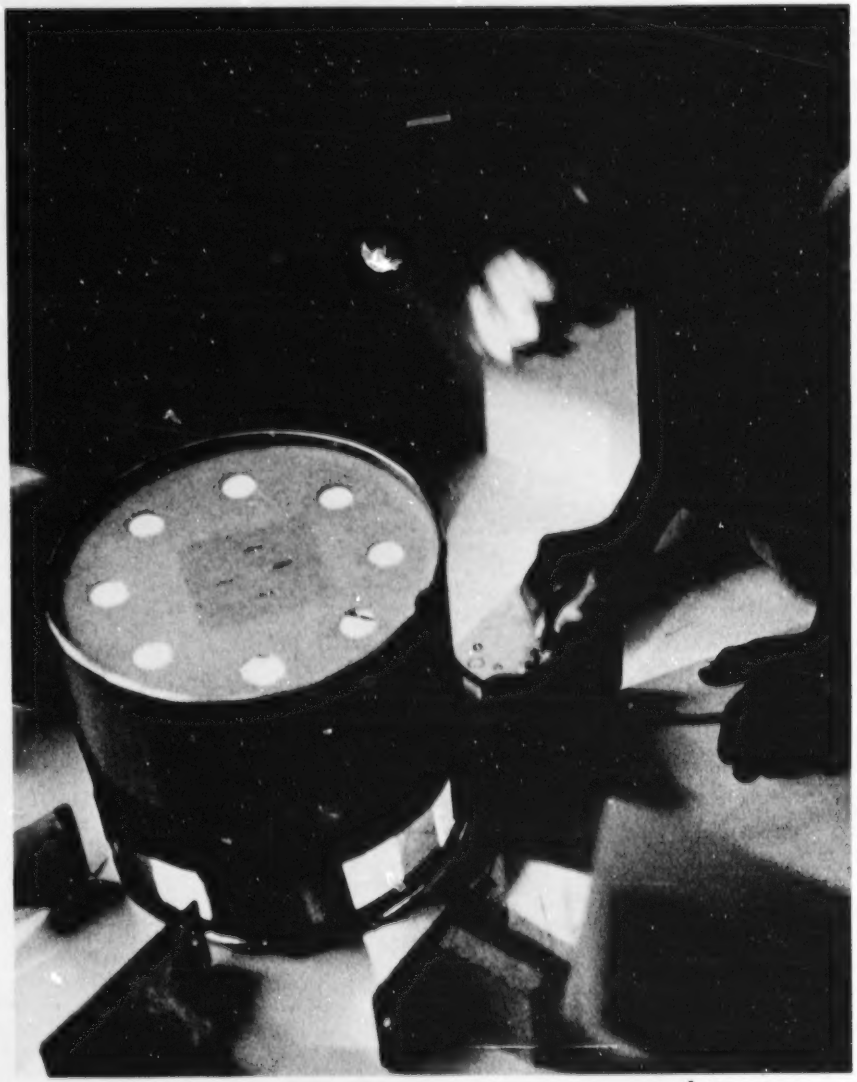
It is possible to make a colored picture which is of one thing (such as a house with open windows) when observed in green light and a different thing (such as a house with no windows at all) when observed in red light.

Also, you can write letters of the alphabet, using different crayons for different parts of the letters, so that the words they spell are different when seen in different lights.

The most extreme examples of the kinds of changes which can be observed can probably be achieved by using red, yellow, and black crayons for the drawing and the red and green beams for viewing. Red and yellow crayons – and white paper, for that matter – look pretty much the same in red light, but the red is different from the other two in green light. Red and black look similar in green light but different in red light. These differences can easily be exploited to get patterns which are different under red and green illumination.

You shouldn't have to tell the students which colors to use to get these changeable pictures. In their work, most students will find the most versatile combinations for themselves.

The students can draw and test double drawings and then challenge each other to predict what their drawings will look like under the various lights.



Transparencies

Try this yourself, and then you may find it useful to involve particular students in the intricacies of these phenomena.

If some of the paper with which they are working is transparent enough, the students can hold up their pictures against the colored masks to be viewed by the light coming through the pictures f n behind. Most pictures look very much the same, whet ewed in this way or just put on the floor in the color n, but there are some interesting things to be obse when the drawings are used as transparencies.

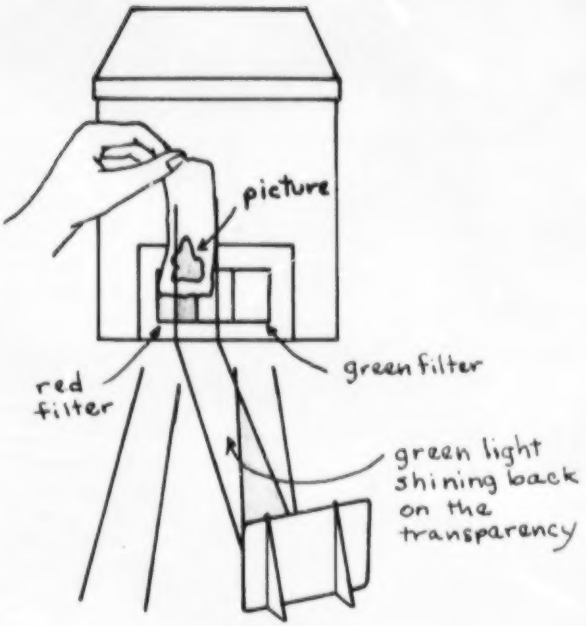
Suppose a student has a crayon drawing with reds and yellows in it. You can ask him –

What will that picture look like if we hold it up against the red plastic?

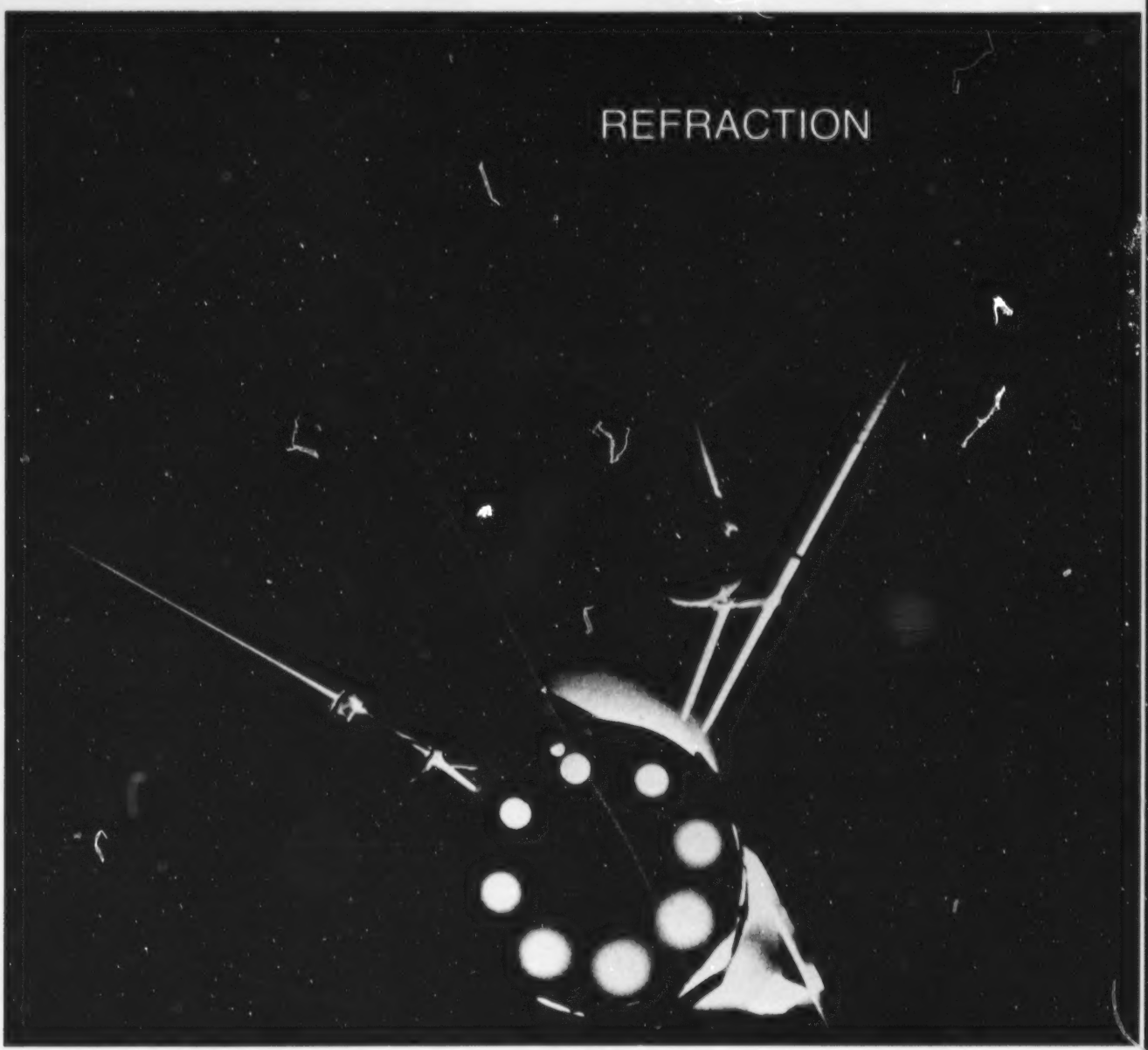
Whatever he guesses, tell him to try the experiment.

What will happen if we shine some green light on it?

Using a mirror, it should be possible to shine some of a green beam onto the drawing while it is held up against the red plastic.



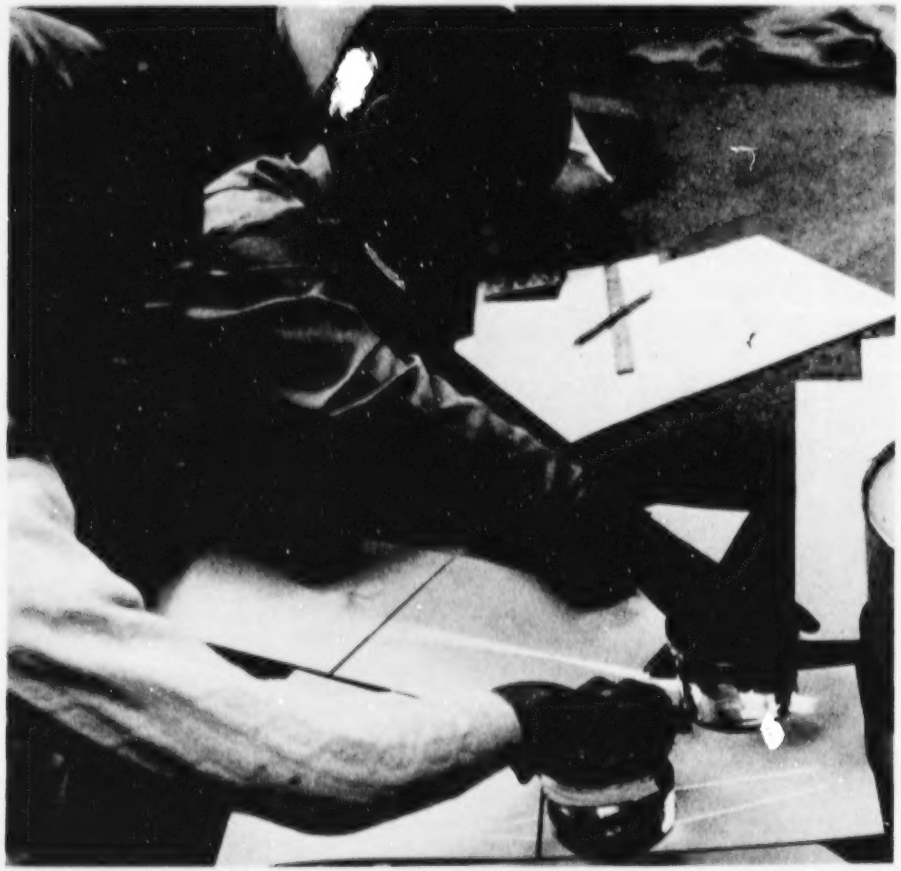
What happens if the drawing is held with the crayon side out as you shine the green light on it? If the drawing is held with the crayon side toward the source, what then?


REFRACTION

VII. REFRACTION: INITIAL EXPLORATION

Time: Probably one session

Equipment: Sources, #1 and #2 masks, plastic containers. For each student: a probe, comb, and screen.



Introduction

This section introduces refraction to your students. When light passes obliquely from one medium (such as air) into another (such as water, sugar-water, or glass), its direction can be changed. This phenomenon is what makes lenses work. It causes some of the distortions you can see when you look through a transparent object. Also, since different colors of light have their paths bent by different amounts, refraction can separate colors and convert white light into a band of colored light.

As in the other parts of this unit, it is best to allow an initial hour for free and undirected explorations.

The mask best suited for free activities is the one which makes two narrow beams and one wide beam. Start out with this one (#1).

Students should be given one of the medium-sized plastic containers, filled so that the water level is up to the threads of the lid. The lid should be twisted on as tightly as possible.

The largest containers supplied in the *Kit* are not watertight enough for general use, but if some of your students want a larger container to implement some idea of theirs, they will find these useful.

The smallest narrow containers can be filled and distributed, one to each pair of students working together.

Probes and screens are to be distributed, but the black plastic combs should not be passed out at the beginning. Have them handy for distribution during the period.

Equipment Handling and Precautions

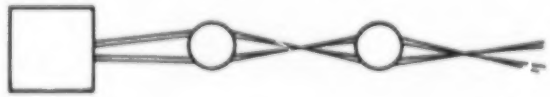
The sources have probably been in use for many hours, and the bulbs should be inspected before you begin this work. Any bulb with a bad filament (see "Equipment," page 3) should be replaced.

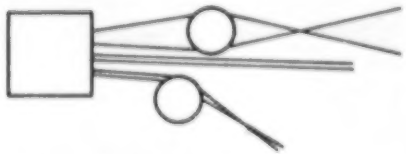
The plastic containers should be filled before class if possible. If you can store them between classes *without emptying them*, it will save you a lot of time. Your students may be cautioned not to turn the containers over or handle them roughly. The lids help, but they are not completely watertight. Paper towels can be put in piles around the room near the work areas to wipe up small spills as they occur.

In order to try some special idea, a student may want to empty a container or work with the lid off. If he uses a little care, this need not cause too much of a mess.

Getting Started

When they have their equipment and the sources are turned on, your students will begin to put the containers in the beams, move them around, and see what happens. These sketches show some of the arrangements they will set up:





They will see that light sometimes bends or changes its direction when it enters or leaves a container. Often some light will be reflected and will not enter the water. The students will sometimes observe colors in the beams of light coming out of the containers. Often these beams are quite dim, but when they are observed closely, they will be found to have all the colors of the rainbow.

The students should spend as much time as possible exploring the possibilities of the equipment. You can challenge them with questions:

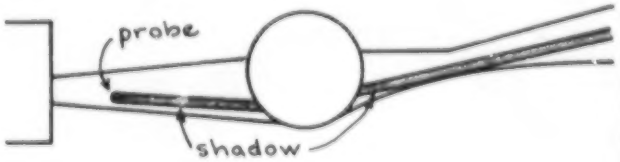
Can you put your container in the light from the source so that the light doesn't bend?

Can you make your two narrow beams come out parallel?

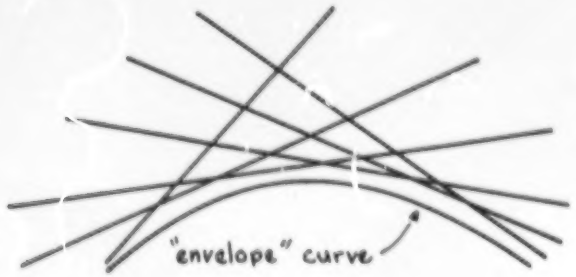
Can you get colors from a white beam?

One of the most perplexing things that will be observed will be a beam of light apparently following a *curved* path across the floor in an arrangement like this:

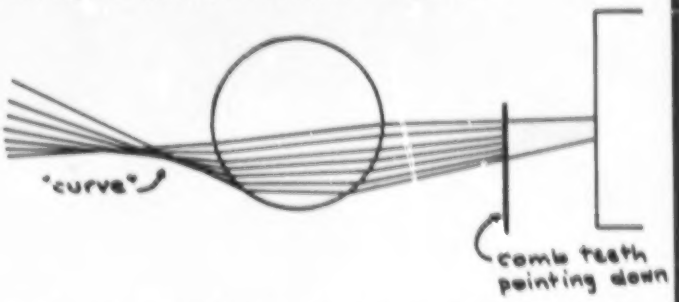
If students are interested in this, suggest that they put their probe sticks into the beams and move the sticks around between the containers and the light sources. They will see the effect of a container on the resulting shadow and will begin to understand how an apparent curve can be made up of many straight lines. The probe stick will essentially draw, with its shadow, the various straight lines that make up the curve.



Many straight lines can be drawn in combination to form an apparent curved line, called an "envelope" curve.

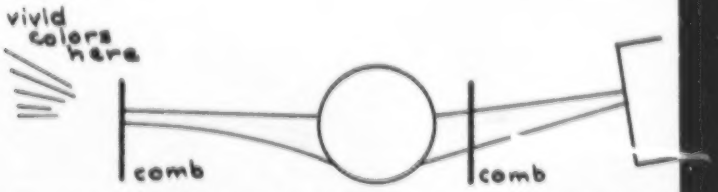


Black plastic combs can be passed out to the students whenever they seem to be ready for something new. The teeth of the combs cast many shadows, turning a wide beam into many narrow ones. This is particularly useful in connection with a "curve." When they hold a comb in the light as shown, the students will see this:

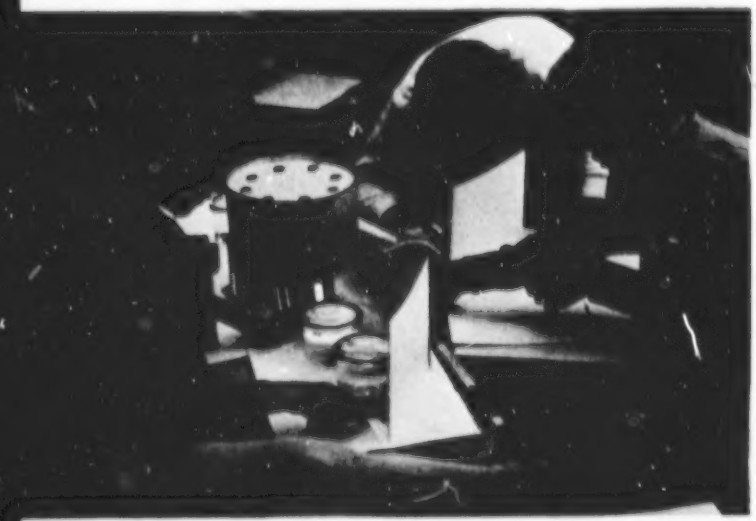


The curve they saw previously will clearly be shown to be made up of many narrow straight beams of light. The students can clarify *any* confusing effect of the wide beam going through the containers, either by using the probe stick to cast a narrow shadow or by using a comb to break the wide beam into many narrow ones.

One of the most striking and most beautiful effects of all results from using the combs in a special way. A student might discover this, but if not, be sure to show it to your class. If you hold one comb between the container and the source and another comb on the other side of the container, as shown in this sketch, very vivid colored bands will appear.



These bands move and change as the combs are slowly moved back and forth and tilted.



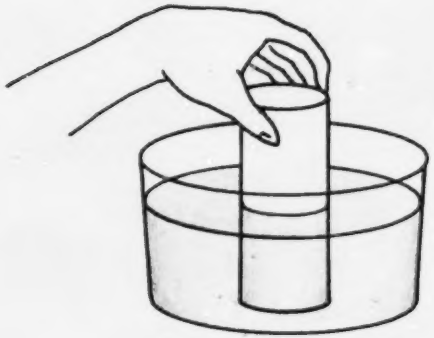
Special Activities

In some classes, individual students have gone on to other activities. For particularly interested individuals, you may want to make specific suggestions along the following lines:

1. The precise way the beams travel can be traced on large pieces of paper put under the containers. These drawings will show how the light bends when it enters and leaves the containers. The path of the light inside the containers can also be shown in such drawings. This helps students see exactly where the bending occurs. Before doing a drawing, a student should tape down the source to keep it from moving if it is bumped.

2. An empty, small container held down in a large container filled with water makes a very interesting object to hold in the light beams. Of course, you must watch out for spillage and not fill the outer container too full when doing this.

The inner container can be filled, too, so that students can see what happens when both are full. A particularly interested student could usefully explore these combinations and perhaps make tracings or sketches of what he sees.



3. To some extent, empty containers can be interesting to work with. With careful attention to details, a student can examine the ways in which the light passes through the plastic itself.

VIII. REFRACTION: COLORED LIGHT

Time: One session

Equipment: Sources, #2 and #5 masks, large containers, white paper, pencils, and rulers. The #2 masks should be inserted in the sources.

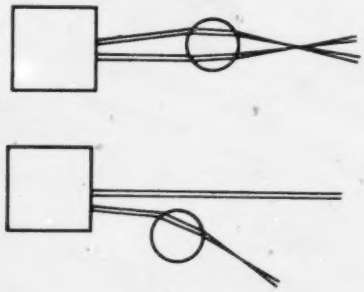
Introduction

This is a difficult session; it has worked very well in some trial classes and not well in others. It takes careful work to see the intended effect. Some teachers said that it was too "fussy," while others found it valuable and interesting, even though not all their students were careful enough to carry out the work completely. Try the activity yourself first, see what is involved, and then decide how to use it in your class.

The sources must be taped down firmly, and all faulty bulbs must be replaced.

Experiments

This set of activities is designed to help students understand how colors are produced when white light is passed through the containers. First, the students should be asked to make a setup in which they can clearly see one or two narrow white beams being bent by a container. Arrangements may be like these:



Now, you can pass out the colored #5 masks and ask the students to see how colored beams are affected by the containers.

The #5 mask should be *held* in the beams and should not be inserted in the source slot. The students will see essentially the same patterns of light, only the beam or beams will be colored instead of white.

They can hold first the red #5 mask in the beams, and then the green and blue.

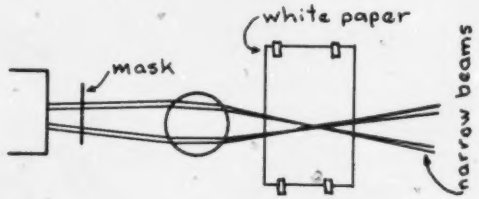
The different colored beams may seem to be bent by the same amount; in fact, they are not, but the differences are very small. You can ask the students to look at this:

> *Can you do a very careful experiment that will show that red light and blue light are bent by different amounts?*

They can try to invent such experiments, and you can suggest techniques that will show the difference. The class can then try to carry out one or more of these techniques.

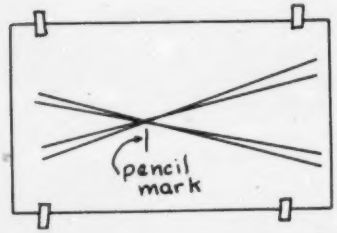
1. The first technique can be presented this way and carried out step by step:

The container should be moved around until the two narrow beams are made to cross at a very distinct point. This takes a little fiddling. A piece of clean white paper should be put on the floor, so that the crossing point of the beams can be clearly seen.



Both beams can now be colored red or blue or green if a #5 mask is held in front of the two narrow slits. The source, the mask, the container, and the paper on the floor should not be moved and, in fact, must be taped down to prevent accidents.

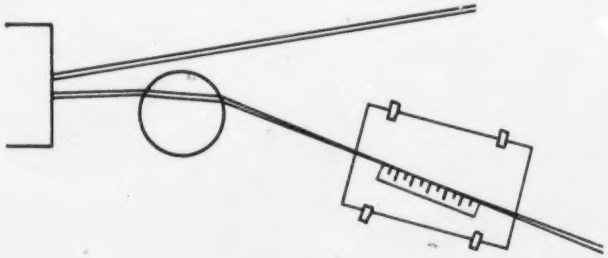
The crossing point when both beams are red can be marked with a pencil like this:



Then, the beams can be colored blue and the crossing point again marked in the same way. If all this is done and observed very carefully, the students will find that the marks do not fall on top of one another, but that, in fact, the blue beams cross closer to the container than the red beams do.

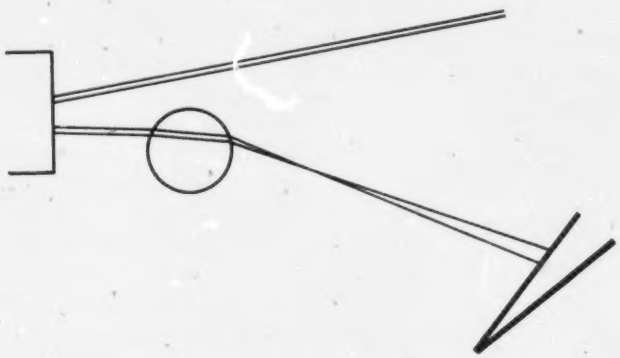
It will take individual students different amounts of time to perfect this technique. Once they have mastered it, they can repeat it in various ways. You can suggest, for instance, that they mark their crossing points by holding the colored plastics in the masks over their eyes instead of over the source slits. Should this give the same result?

2. Another technique was invented by students and is simpler in some ways. With a single narrow beam colored red, the students can trace with a ruler the path of the emerging light.



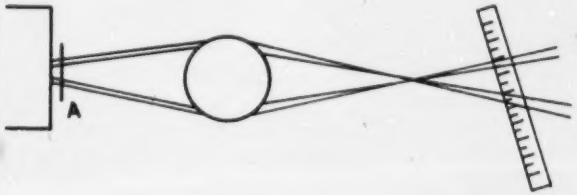
Again, without moving anything, they can make the beam blue and trace its path on the same sheet of paper. The resulting lines will not be the same and should show, as did the first technique, that the blue beam is bent slightly more than the red one.

3. Another way to see this effect is shown here. The difference in the position on the screen where the beam falls when it is red and when it is blue can be marked carefully.



You have to look very closely to see these differences.

4. One student invented this arrangement:



He was able to see that the distance between the beams where they crossed the ruler depended on the single color that he made both beams with a colored mask held at position A.

In the process of carrying out any or several of these experiments, the students will begin to look more critically at what was happening to the white beam in the first place. The white beam, after passing through the container, is colored on the edges and somewhat "smeared out." This effect is due to the fact that the different constituent colors of light within the beam are being bent by different amounts.

In one class in which the students had explored these effects carefully, a lively discussion went on for a full hour. Students discussed the relationship between these observations and the situations in which they had previously seen "rainbows."

White light is separated into its constituent colors by prisms, containers, and, for that matter, moisture in the air, just because different colors of light are bent by different amounts. If all the colors are traveling together forming white before they enter the containers, then afterward they will be traveling in slightly different directions and will separate to give a range of colors or a spectrum.

IX. REFRACTION: CHANGING THE WATER

Time: One or more sessions

Equipment: Sources, #1 or #2 masks, white paper, pencils, paper cups, sugar (or salt), and spoons

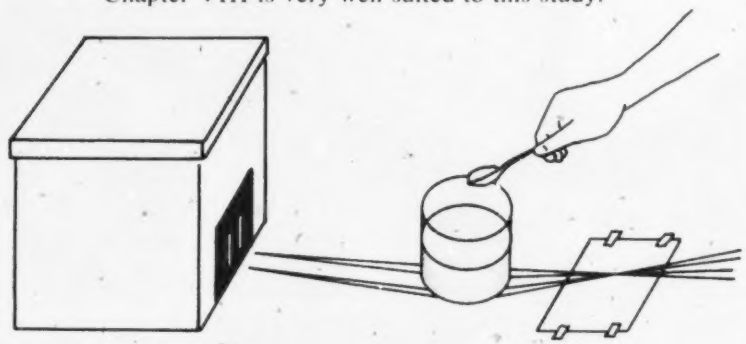
Introduction

Up to this point, the students have been free to change the color of the light and the arrangement of the containers. In order to explore further what happens to light when it passes from one substance to another, it would now be good to try many different liquids in the containers. A convenient and interesting way to change the liquid in the container is to dissolve sugar or salt in the water. Light which enters water obliquely changes direction, and this change is greater if the water contains dissolved sugar or salt.

Some students have found these activities very interesting while others have not found them so. Again, if you have time to go through the activities yourself beforehand, you will be more able to decide how they can best be used for your class.

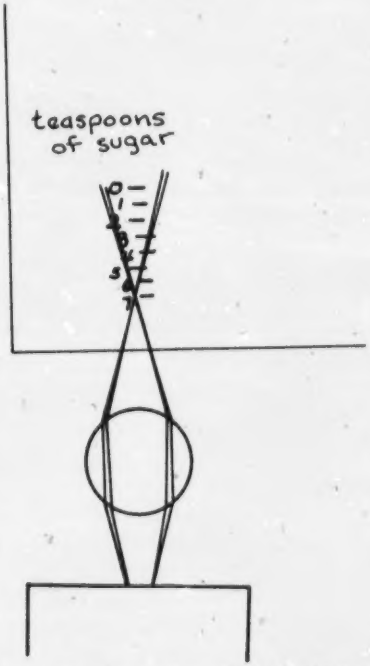
Experiments

An adaptation of the crossing-point experiment from Chapter VIII is very well suited to this study.

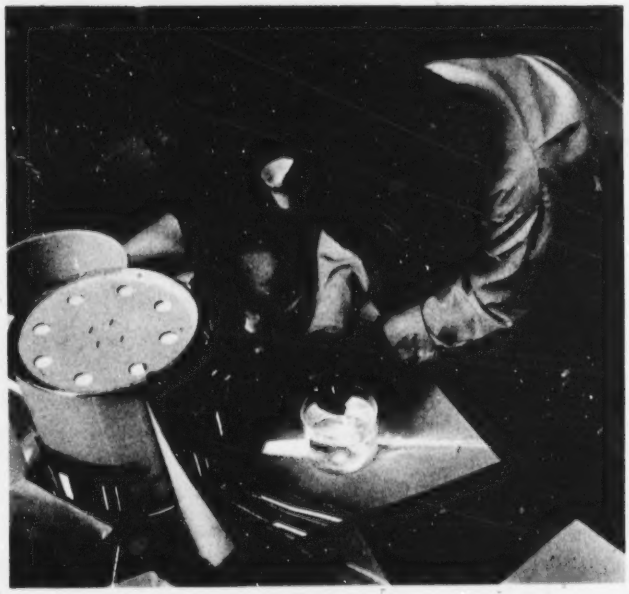


Using a container that is only partially full and without its lid, the students should again find and mark a good crossing point. Now, sugar can be added to the water, about a tablespoon at a time, and a record made of the new crossing point. The paper for recording the crossing point should be taped down.

There are many things to observe as the sugar is added. Immediately after a spoonful is dropped in, the beams will become cloudy-looking. Finally, after many spoonfuls have been added and dissolved, a record looking something like this will be obtained:



An overall change on the order of one-half inch can be brought about with four or five tablespoons of sugar.

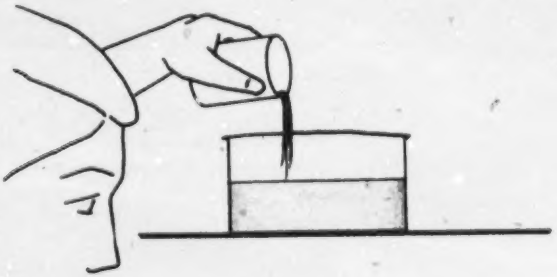


Another way to change the crossing point is to make up, in a separate container, a sugar solution that is very concentrated. That is, in a small container of water, dissolve as much sugar (or salt) as you can. Then, after recording the crossing point for the plain water, pour some or all of the solution into the container, and observe the changes.

A remarkable thing about this experiment will interest many students. When they added the sugar spoonful by spoonful, they probably observed the beams becoming cloudy and not clearing up until the sugar had dissolved or until it had settled, undisturbed, on the bottom. It is quite natural for the students to conclude that the beams are cloudy because of the little pieces of undissolved sugar which get in the way of the light.

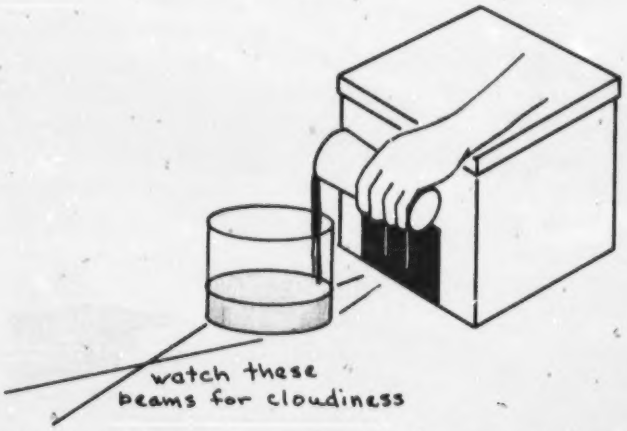
However, in this last experiment, when a clear sugar solution is poured into the clear water, the beams will still become cloudy. They clear up again if the water is either stirred or left alone for a short time. This shows that the cloudiness is not caused by particles of undissolved sugar but is, rather, due to the uneven distribution of the sugar solution in the resulting mixture.

A nice type of experiment which can be suggested to students particularly interested in the cloudy beams is the following: A sugar solution can be made up in the small container. Then two or more beams can be passed through a medium-sized container of water. The sugar solution is then carefully poured into the container, little by little, at a place near one edge. The beams can then be watched for cloudiness as the sugar-rich solution distributes itself in the water.



The students can also just look through the container as they add the sugar solution and see how things appear.

This cloudiness that can be clearly observed in these two ways is very closely related to some other phenomena with which the students are familiar. Why do you need windshield wipers on your car? Obviously, to wipe the rain off. But why should you have to wipe the rain off? Water is transparent, and glass is transparent. You can



see through either one just fine, and yet when raindrops are scattered all over the windshield, you can't see through it very well.

In fact, each droplet has a curved surface and is bending light, just as a curved container of water bends light. This gives you a broken and confusing picture. If the windshield is wiped so as to smooth out the droplets into an even layer of water, then it is as easy to see through as it is when dry.

This is the key to the cloudiness problem when sugar-water is poured into plain water. Until the mixture is throughly stirred or allowed to sit a long time, there are little regions of extra dissolved sugar, and these regions bend the light a little more and tend to spread the beams so they look cloudy.

Another example of this is the "wavy" look above a heater or a hot road. Hot air and cold air are both transparent, but uneven mixtures of the two have many small regions which bend the light passing through them. Therefore, any beam gets spread and becomes fuzzy, since different parts of it are bent by different amounts.

APPENDIX

BACKGROUND: COLORED LIGHT

Colored Light Mixing

Note: The following background material is for your own use and is not intended for classroom presentation.

During work of mixing colored light, there is one perplexing and fascinating question which will come up over and over again. Most students will have had some experience with the mixing of pigments, and they will be faced with a real dilemma. In their minds, the "primary" colors are red, yellow, and blue. From these they can get all the other colors in the familiar ways—for example, blue + yellow = green. With light, things will seem to be changed around. Students can get, effectively, all colors (including yellow) from red, blue, and green. What is going on? How are the two types of color mixing related?

Consider, for a moment, the colors yellow and green.

Yellow is observed when students:

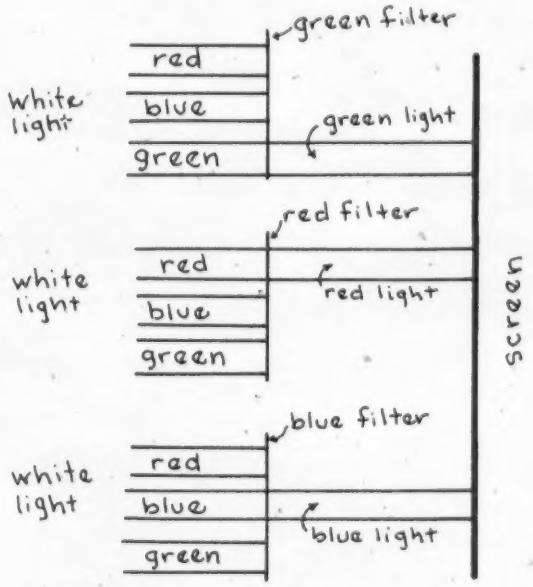
1. Mix red and green light on a white screen
2. Make a yellow shadow—that is, mix red, green, and blue light, and then block off the blue light with a probe or other object
3. Simply look at something that is yellow (such as yellow crayon or paint or paper) in normal light

What about green? To see green, the students can:

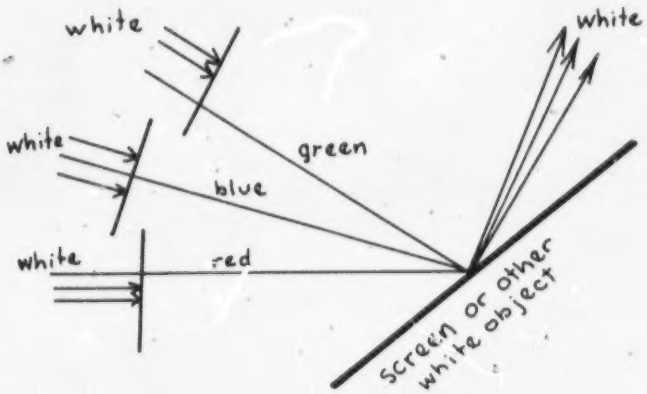
1. Look at green light shining on something like the screen
2. Mix yellow and blue pigments
3. Simply look at something that is green—green paint or a green object
4. Make a green shadow

What is the relationship between colored light and pigment?

For simplicity, imagine that white light is always a mixture of three colors of light—red, blue, and green. (In fact, it usually contains a mixture of many shades in a continuous band from violet to deep red.) A "perfect" green filter would stop all but the green part of white light from passing through it. All three filters might be shown like this:

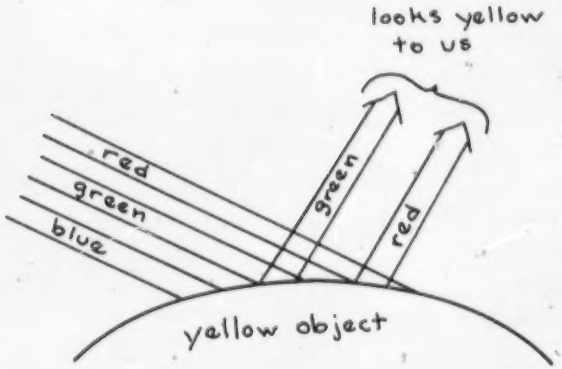


If we take the light coming through all three filters and mix it together, we see white light again.



Now, what do we mean by yellow? If we see a mixture of just red and green light coming from a spot, we say that spot is yellow. Most of the time, that is what we mean by the word "yellow." You can say that every yellow object around you is giving off a mixture of red and green light. (Some objects give off "yellow" light. That is, there exists a certain kind of pure light which is also called "yellow." Most familiar objects give off a lot of red and green even if they also give off a "pure" yellow.) We see this yellow when we mix red and green light on the screen.

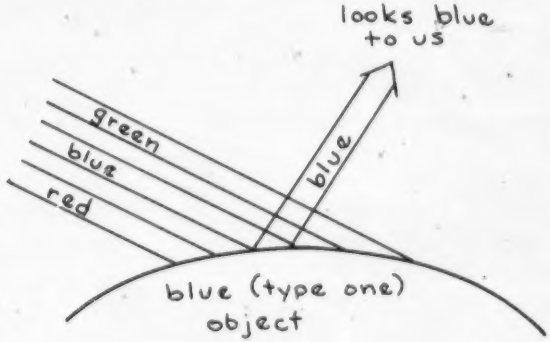
So why is some object yellow? We say an object is yellow, usually, because it absorbs blue light. White light (that is, red, green, and blue light) is falling on it. It keeps or absorbs the blue light and reflects or gives off the green and red light that hit it.



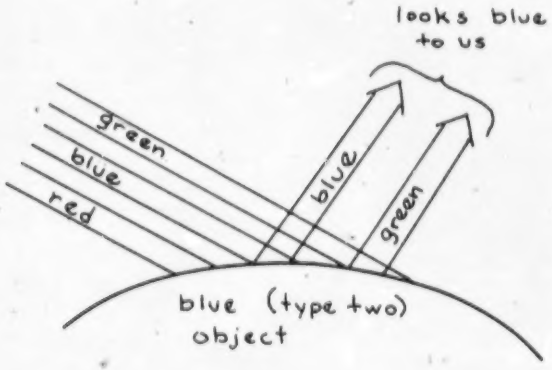
So, you can think of a yellow object as something that swallows up blue light.

What is blue pigment?

If something looks blue to us in white light, you might reasonably decide that it must absorb or swallow up red and green light.



There are blue pigments that do this, but most blues that we know aren't quite like this. They don't swallow up the green light this well. So, we might represent it this way:



So, think of a blue pigment as a red-absorber.

Now what will happen if we mix together a blue type-two pigment with a yellow pigment. They can both function, even though they are mixed together. The yellow pigment absorbs the blue light, and the blue pigment absorbs the red light. What is left to bounce off into our eyes? Green light. So we see the mixture as green.

This explanation is oversimplified. White light is *not* just blue, green, and red. Yellow pigments do *not* precisely remove all the blue and reflect all the green and red. The abundance of hues and depths of colors and the infinite sublety of our color experiences testify to the true complexity of these phenomena. In fact, there are some circumstances in which our experience of color is not like that described here at all, but, as a starting point to pin down some of the most simple color experiences we have, this explanation will do.

Ranges of Color

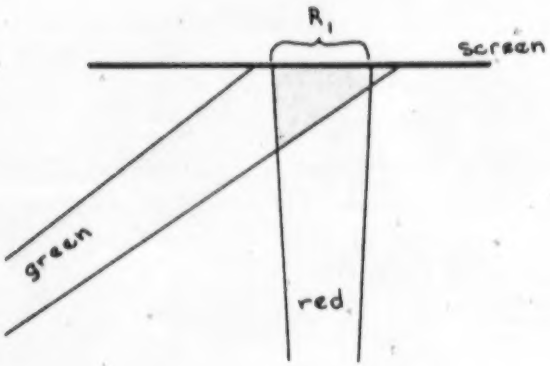
As you observe the mixing of colored light, you will see a great variety of colors. You might think that only seven colors are possible because there are only seven ways to use red, green, and blue beams singly or in combination:

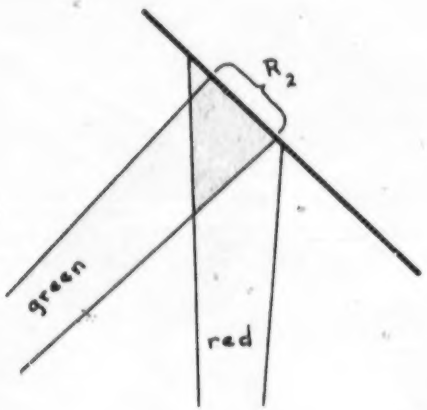
1. red
2. blue
3. green
4. red + blue
5. blue + green
6. red + green
7. red + blue + green

In fact, however, you will see one student obtain a greenish-yellow while another gets an orangish-yellow. Somehow, a very wide range of colors is possible from mixing these three beams, and the following explanation should make it easier for you to suggest ways to help your students experiment with subtle changes in color.

Consider, for the moment, the mixing of red and green light. A lot of red light mixed with a little green light should give a yellow which is reddish. Likewise, a lot of green light mixed with a little red light should give a greenish-yellow. In fact, it should be possible to see a continuous range of colors going from red to green with yellows in between.

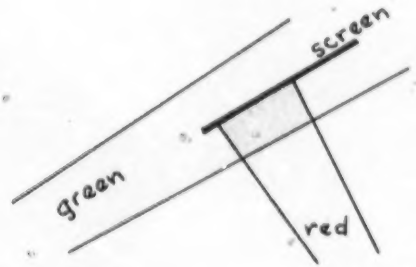
How can the light mixtures that are possible with this equipment be varied? It is very simple. Consider the following two situations.



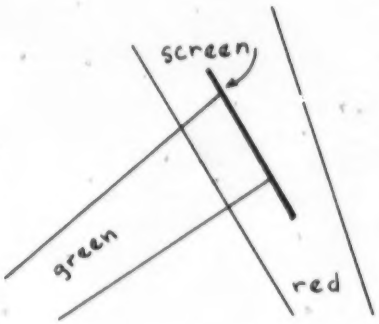


In both drawings, a red and a green beam are hitting the screen, and the regions where they both land on the screen (R_1 and R_2) will look yellowish, but R_1 will be a reddish-yellow, and R_2 will be a greenish-yellow. Why? Think of the red beam as having just a certain amount of light in it. In the first sketch, this light is all delivered into region R_1. In the second sketch, it is spread out over a much larger region on the screen. Therefore, there is less red at any one spot, and so the green dominates the red in the second mixture. In the first mixture, the red dominates the green.

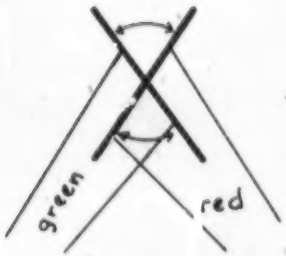
Now look at a variety of different situations.



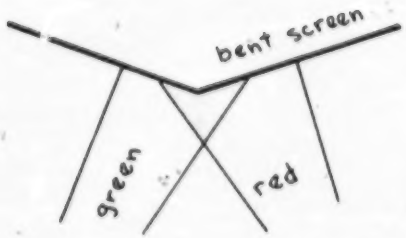
No green light will fall on the screen face. It will look pure red.



Here the screen will look green.



Rotate the screen back and forth between the two extreme positions in the preceding two sketches, and you will see the color gradually transformed from red to green and back.

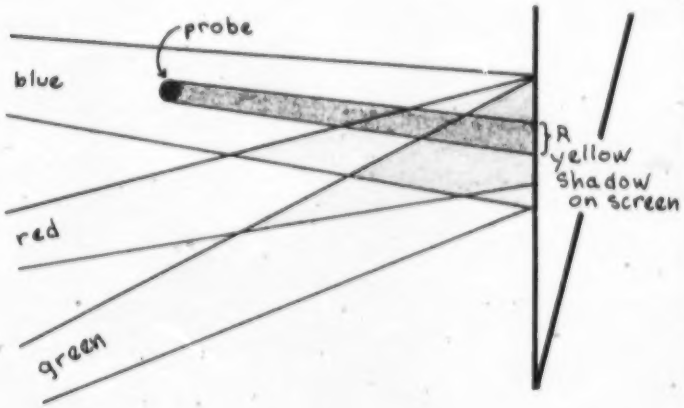


With a bent screen, you will see two different yellows on the two sides of the fold in the screen.

Using complicated objects (such as your own hand) as three-dimensional screens allows you to look at a whole new range of effects. The bent screen is a start toward this.

Pigments, Colored Shadows, and Colored Light

Pigments serve their colorful function by selectively absorbing some colors of light and allowing other colors to find their way to our eyes. It is interesting to note that the thing in the colored light-and-shadow work which acts most like a yellow pigment is a probe stick casting a yellow shadow.



If it weren't for the probe stick, the region on the screen marked "R" would reflect or give off red, blue, and green light into our eyes. The probe stick stops the blue light, just as a yellow pigment absorbs it, and, as a result, we give region R the color name "yellow," because only red light and green light are coming from that spot into our eyes.

By looking at pigments as things that selectively absorb different colors of light, we can begin to understand why, for instance, a yellow object might look very

dark in blue light or a red object might look black in green light. If a red object swallows up green light, and the only light falling on the object is green light, then essentially no light will bounce off it into our eyes. Hence it will look black.

Here's another case to consider. Red and yellow pigments both reflect red light. The red pigment swallows up green and blue; the yellow pigment swallows up blue. So if both are illuminated by red light only, you would not expect them to look very different. They both treat pure red light the same way, so in red light they look the same. There is no need to go through an exhaustive analysis of every possible combination of colors. The point is that the pigments are most easily understood in terms of the colors of light which they happen to absorb and the colors which they reflect.